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Computational model for heat transfer in the human eye using the finite element method

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COMPUTATIONAL MODEL FOR HEAT TRANSFER IN THE HUMAN EYE USING THE FINITE ELEMENT METHOD

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Abstract

In this work a finite element model for the human eye presented. Thermal analysis was done in order to capture the temperature variation in the human eye. The model was created using advance finite element program ABAQUS. In the model each of the eye's component (cornea, sclera, lens, iris, aqueous and vitreous humor) has own material property. Specific boundary conditions were used for the model. The model incorporates the interaction between eyes components. The Comparisons were done with the available experimental results. The results show that there is a temperature variation in the human eye components with the increasing the time. The front of the cornea and back of the cornea shows different temperature value. And the result shows that there is also temperature difference between the peak of the posterior surface of the cornea and the adjacent posterior surface of the cornea to the sclera.

Chapter 1. Introduction

1.1 Introduction

Temperature has a profound effect on the eye. The ocular surface has to cope physiologically with the imposed thermal stress of an environment that may change by more than 60 C° which could dramatically affect cellular mechanisms. For example the thickness of the cornea is dependent on the endothelial cells which line the back side of that tissue and the enzyme systems within these cells that control the corneal thickness of the cornea are very temperature dependent, blood flow, which responds to temperature, may be affected adversely in these widely varying conditions. However, temperature monitoring of the interior of the human eye in vivo is not possible, and the engineering models that have been developed have not included the tissue material properties or interfacial behavior between different adjacent tissue that would allow predictions of the heat flow to be made with needed accuracy (Enrique, 2002; Sluzalec Jr., 1985; Scott, 1988; Lagendijk, 1982; Horven 1975;Fujishima 1996; Mapstone[1], Mapstone[2] and Mapstone[3], 1968; Beuerman, 1978).

To develop the level of understanding to arrive at a predictive description of heat flow in the human eye, the following studies were carried out: a- Each tissue or fluid compartment of the eye was represented by its appropriate thermal parameters; b-Realistic boundary conditions were set up which considered the cornea and the immediate surrounding tissue as well as the interface thermal conditions between adjacent tissue; c-Realistic environmental situations with the temperature extremes that are encountered by humans in different environments were included; d- A tight mesh model that revealed local temperatures changes in the various tissue and fluid compartments of the eye were used.

Temperature changes can affect tissues in several ways; it can kill cells, denature proteins causing a loss of function, temperature can slow down or speed up metabolism of cells and be involved in pathological changes of the eye (Zeiss, 1930; Huber, 1960; Gros, Bronner, and Vrousos, 1967). Pain is apparently one sensation that is due to temperature changes in the cornea but the temperature changes witin the tissue have not been well understood and this study may lead to an understanding of studies in this area pain in the cornea (Lagendijk, 1982; Beuerman and Tanelian, 1979). This would be valuable, as it will develop a better understanding of how pain from sensory nerves develops in all surface epithelia tissue.

Current surgical methods for correcting refractive errors of the eye use lasers, which are known to cause local, heating and potentially could lead to loss of corneal clarity as well as opacity of the lens (McCally, 1983; Ishihara, 2001), (Tsutomu, 1991; Al-Ghadyan, 1986). By developing an advanced model of heat flow in the eye it will be possible to understand temperature distribution after thermal events including laser light interaction.

In general, experiments to answer these questions cannot be carried out on the human eye. Therefore, investigators have utilized animal tissues where appropriate to conduct experiments using the rabbit, pig and monkey as they have tissue attributes that are very similar to the human eye. In general, material properties have been obtained from eyes from these animals and from human tissue when available. However, most human tissue has the problem of being much older from the time of death whereas animal tissues can be obtained freshly. In addition, due to the computational complexity many previous studies in this area have allowed most tissues of the eye to have the material properties of water; however, it has been found that there are large differences in the some of the tissue properties and those of water. The present study will be one of the few that have allowed most tissues of the eye to have individual material properties and thus the model should have much improved predictive ability.

In this study, a finite element model was presented for the heat transfer in the human eye. Attention was placed on the cornea as the cells are particularly temperature sensitive (Mishima, 1961) and it comprises most of the revealed surface of the eye. The result that this model provides is compared with experimental results that were previously conducted by (Beuerman, 1979). This will answer a number of important issues regarding heat flow in the eye, and some results considering dynamic heat flow will be shown.

1.2 Background

Intensive research is conducted in order to understand and simulate the thermal behavior of the human eye by analyzing different parts of the eye. In these efforts, finite element methods are used to simulate the temperature distribution in the human eye. A finite element model of heat transport in the human eye was presented by (Scott[1] 1988) .The model was based on the bioheat transfer equations. In that model it could be seen some temperature distribution of the human eye with ambient temperature of 20 C^o and blood temperature $37C^{o.}$ The model took in consideration steady-state temperature variation in the human eye when exposed to microwave radiation, but the analytic method of solution did not take in consideration transient temperature variations in the human eye. Another finite element method was also introduced by (Scott[2] 1988), where temperature change in the intraocular media in the human eye were calculated when it is exposed to infrared radiation. The model considered both transient and steady state solutions. Scott[2] showed that the temperature variation in the anterior segment of the eye can occur if an increase in evaporation from the anterior corneal surface and rapid blink factors appear simultaneously. The models that were just mentioned above were obtained without including blood flow in the iris and ciliary body; this is a deficiency in the model. In the literature, one of the models that were presented earlier is the simple heat transfer model to analyze thermal effect of microwave radiation of the human eye (Al-Badwaihy and Youssef, 1976). The model used an analytical approach for the solution of the steady-state temperature variation. A computer model was developed based on the finite difference method (Lagendijk, 1982).

There was a report that the incidence of cataracts that had increased in glass workers due to the long time exposures to infrared radiation (Meyhofer, 1886; Robinson, 1903, and 1907; Legge, 1907). It is unknown exactly what causes the occurrence of cataracts but infrared radiation may be involved. Some researchers believe that thermal effect can induce cataracts; other believes that it is the result of other biological and genetic issues. It is assumed that infrared cataracts are the result of the absorption of the infrared radiation, which is absorbed first by the iris and than transmitted to the lens (Goldmann, 1993; Pitts and Cullen, 1981). According to theory of (Vogt 1919) infrared cataracts are the results of direct absorption of radiant energy by the lens. (Jordan 1968[1], 1968[2]) discussed potential damaging effects of the light on the eye and protection against damage. The cornea, lens and retina have been shown to be susceptible to damage from light in the ultraviolet, visible and infrared range The effects of light on the human eye was considered to be as a mechanical, thermal or photochemical effect. It was noted that to have a mechanical or thermal effect or injury in the human eye, there should be a high intense light exposure. The cornea and lens are major filters, allowing only a small portion of the incident radiation to penetrate to the retina. The anterior segment of the eye is sensitive to injury from ultraviolet rays. Although ultraviolet rays are absorbed in the cornea, produced experience to high flux density can cause cellular damage secondary to nuclear fragmentation in the corneal epithelium.

Using finite difference method, (Taflove and Brodwin 1975) were able to obtain transient solutions for intraocular temperatures in a microwave-irradiated human eye. In that model the initial temperature was assumed to be 37 C^o and with uniform distribution in the human eye; however, their assumptions are incorrect for the transient solutions. Due to this simplification, their model did not include the body-core and the ambient temperature, which are very important for temperature variation in the human eye (Scott, 1988). (Lagendjik 1982) showed steady solutions for human and rabbit eyes by using the finite difference method .The shape of the eye was approximated. There are two main thermal effects that determine the surface temperature of the cornea, the internal and external temperatures. To be able to partition the influence of those effects the analysis becomes more complicated. The effects on corneal and pericorneal temperature of lid closure and opening (Braendstrup, 1952; Schwartz, 1964), environmental temperature (Schwartz, 1965), and inflammatory ocular disease (Huber, 1960) have been previously investigated. The effects on corneal temperature due to ocular inflammation were also investigated by (Zeiss 1930) using a radiometric method. A bolometer was used to measure the corneal temperature by (Mapstone 1968). The calibration scale used was able to read from 26 C^o to 4 C^o in units of 0.1 C^o and the bolometer was sensitive to capture infrared radiation in the range of 1 to 25 microns. In his work the following factors were investigated: environmental temperature, lid retraction, lid closure, blinking, tears and tearing, anterior uveitis, carotid artery disease, and posterior segment pathology. The range of the environmental temperature was 18 C^o to 27 C^o and it was seen that there was a linear drop in the corneal temperature with an average decrease of 0.145 C^o. In the work of (Schwartz 1965) this drop of temperature was 0.23 C^o for the rabbit eye. This difference thought was due to frequent blinking of the rabbit. The reason for having this difference in corneal temperature of the environmental temperature effect is mainly because of convection and radiation. The conduction effect could be ignored since air is a poor conductor of heat. Closure and opening of the eyelids show different variations in corneal temperature, the rabbit blinks much less frequently than human. The temperature raised 1.5 C^o when the eyelids are open and decreases 1.1C^o when the eyelids are closed (Mapstone, 1968). When the eyelids are open the cornea surface temperature is controlled by convection and radiation. When the environmental temperature becomes lower than the corneal temperature, heat loss from the corneal surface occurs because of convection and radiation. When the eyelids are closed, this heat loss is prevented. In the case of eyelid closure the cornea temperature is influenced by another thermal effect, the vascular palpebral conjunctiva, which is protected from coal environment that may prevail since the perfusing blood has a temperature close to the body core (Mapstone, 1968). It was observed that the temperature of the cornea decreased by 6.6C^o – 5.5C^o when blinking was prevented it decreased by 0.7C^o and 1.1C^o. These experimental results were taken with the assumption that there is no effect from the tears. The effects of the tears on the cornea temperature were not included, while the experiment was conducted, by washing the tears (Mapstone, 1968).

There are four types of temperature effects on the corneal temperature. These effects are: small amount of heat loss between blinks, due to active heat transfer when the cornea is exposed due to the lucking of the tears across the surface of the cornea, and the cooling effect caused by the movement of the eyelids. To be able to reveal and understand the overall effect of these factors, one needs to conduct an experiment which and includes all these four factors that were mentioned above. It is assumed that when the environmental temperature is lower than the corneal temperature, heat loss from the cornea occurs more rapidly. One of the main reasons of this kind of heat loss is assumed to be the evaporation from the tear film. Therefore, when the environmental temperature increase over body core temperature or corneal temperature, evaporative heat loss does not occur since one would not expect any tear film evaporation. On the contrary, instead of expecting evaporation in this case, one would expect a temperature increase in the corneal surface temperature.

The tears may cause an instant change in the corneal temperature while the other effects that mentioned previously need more time to have an effect on the corneal temperature. In the experiment that was conducted by (Mapstone 1968) with taking temperatures with the bolometer, the corneal temperature increased up to 1.0 C^o. The reason for this kind of increase in temperature was because due to either voluntary lid retraction to expose the necessary amount of the cornea or by manipulation of the lids by the experimenter. Tears may have also a cooling effect on the cornea if they evaporate from the pre-corneal film. The superficial oily layer of the pre-corneal film protects against evaporation from the inner fluid layer, (Mishima and Maurice, 1961). It was shown experimentally that any imperfection in the oily layer causes the increase in evaporation rate between 2.2-3.7 $\mu l./hr.cm^2$ to 40-45 $\mu l./hr.cm^2$. Humidity is also one of the effects that cause evaporation, which was found to be a small quantity, 1 per cent. It also causes cooling effect on the cornea (Schwartz, 1965). Humidity causes a change in the corneal temperature of 0.04 C^o. The overall effects of tears on the corneal temperature are two: first, the cooling effect because of evaporation of tears from the pre-corneal film, second, a heating effect because of the secretion of warm tears and their path across the front of the colder cornea. If there is normal secretion of the tears in the eye, it is not expected to be an effect from the tears in the corneal temperature.

On the back or inner side of the cornea, aqueous humor controls thermal flow. The aqueous humor is always closer to core temperature than the more superficial cornea. There are two factors that affect aqueous temperature; first, the difference between the amounts of the heat lost in the cornea and the amount gained from metabolic activity, and the vascular supply to the anterior chamber. Convection and blood perfusion have an effect on aqueous humor, and as a consequence of it, aqueous humor will affect corneal temperature. Increase blood perfusion will increase corneal temperature increase; this conclusion was obtained after an experiment was conducted for the measurement of the corneal temperature in anterior segment inflammation and carotid artery disease (Mapstone, 1968). The increase in the blood supply in the anterior segment may increase the corneal temperature up to 2.4C$^{o.}$ A decrease of the blood supply in the anterior segment and in the carotid artery disease may reduce the corneal temperature up to 1.3 C^{o}. The effect of the metabolism and blood supply may also play a role in changing the corneal temperature. It should be noted that the increase in the blood supply to a tissue results not necessarily in the local temperature increase. The change in corneal temperature is assumed to cause not equal distribution in blood supply of the anterior segments. The posterior segment is considered to have less effect on the corneal temperature (Mapstone, 1968).

In all of the mathematical models of biological systems, finding appropriate numbers of parameter presents a problem, and this becomes particularly important when the model is used for different subjects and different physiological and environmental conditions .In general, because of the lack of the accuracy of the material parameters of the human eye, it is assumed and accepted that its material parameters are close to those of water parameters since in all biological tissue water is main component. Therefore in many models of the eye the assumption is made that it is homogeneous and that the material parameters of the eye can be approximated to those of water. However, heat flow across the thin (~ 0.5 mm thick) cornea has been shown to be significantly lower than if the same layer consisted of water (Beuerman, 1979). One of the main reasons for the lack of accurate material parameters of the eye is the difficulty in conducting direct experiments on the human eye. Instead, properties of animal eyes have been measured. A porcine eye was tested by (Kampmeier 2000) and **(**Sporl 1997**)** or on rabbit eye by **(**Tanelian and Beuerman 1984), a cow eye was used by (Trumbley 1991) in his studies. The reason for using an eye for these animals is because of their similarity and having close material parameters to those of the human eye. Another reason for not being able to conduct suitable experiments is the complexity of the eye and behavior of the eye and the small size. In spite of these difficulties, researches have tried to understand and define the thermal behavior of the eye and its components by using finite element methods with various computer programs and simulations. The corneal temperature measurement was performed by (Mapstone 1968) using contact thermometry. However, this presents some theoretical problem due to the symmetrical thermal environment.

The cornea is the major refracting optical element of the eye focusing light onto the retina. In addition, the cornea has the function to protect and ensure visual function upon which our lives are extremely dependent. The cornea is a vital part of the eye for two reasons. The first commonly known use of the cornea is that it is the major refracting optical element of the eye. In addition to playing a role in vision, the cornea also contains sensory nerve endings in the outer layer (the epithelium) that register a change in temperature or mechanical disturbance and sends signals to the brain to trigger a protective response such as the blink reflex. (Beuerman and Tanelian 1979) found that whether the stimulus is thermal, mechanical or chemical, the activation of the corneal nerves is sensed as an unpleasant or painful experience. Little is known about the mechanisms that cause the nerve endings to register the initiation of pain. The reliable prediction of the material behavior of the epithelium layer requires the development of basic constitutive relations, which include the effect of microstructural changes. These are due to the individual effects of non-proportional loading, and elevated temperature as well as the coupling of these two effects. Because of the importance and role of the cornea for vision, this work is mainly presenting heat flow through layers of the cornea and consecutively the effect of heat flow through the cornea on the other parts of the eye. One can understand the importance of defining the behavior and response of the individual tissues of the eye. This understanding of the thermal behavior of the eye will help to anticipate more fully the response from laser light and the effect of the wide range of thermal environmental on the eye.

1.3 Methodology

Numerical studies were conducted using a computational model for the finite thermal analyses of a cornea subjected to different thermal and mechanical loading cases. A detailed mesh is used so as to create a finer mesh in region where thermal effects may be more severe, and a coarser mesh elsewhere that needs to be incorporated in the finite element analysis. The computational model was included in an existing finite element code. ABAQUS Standard was used as a software package. ABAQUS is an advanced finite element program.

The mesh overlying the human eye model was created using the mesh technique that ABAQUS Standard software provides. Components of the eye were meshed separately and then merged taking into consideration the juncture between those parts. The mesh that the software package provides as a result of this research may provide a useful tool for other researchers to carry out similar investigations on other complex tissues.

Initial conditions of the problem were adopted to be 37 C^o for the whole eye. The required material properties for this study include the density, thermal conductivity, and the specific heat. Thus, we were able to provide each component tissue of the eye separate material properties, which have not been previously attempted. All these material parameters were used in this work and compared with material parameters that are used by many researchers. The result obtained from this work is also compared with available experimental results for further investigations.

1.4 Objectives

The main objective of this study was to determine the temperature distribution in the human eye. This can help to analyze and understand the thermal behavior or heat transfer through the eye. The temperature variation in the human eye was obtained using the finite element method. The use of computational software for analyzing the thermal characteristics of the eye may help supplement the experiments currently conducted by researches on the human eye.

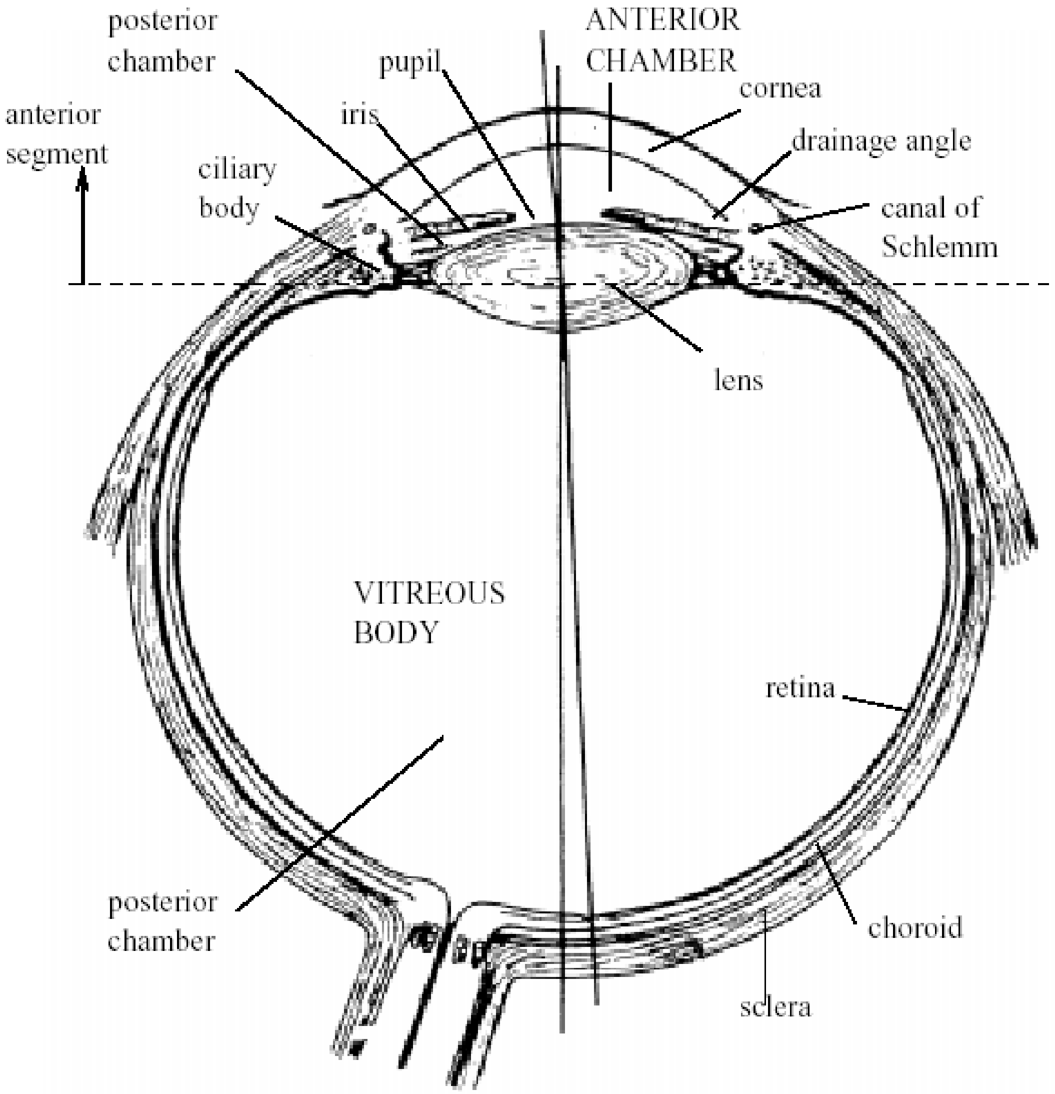

Fig.1.1 Components of the eye with details.

In particular, the following objectives were studied in this work:

- Temperature distribution in the cornea
- Temperature change in the core of the human eye
- Temperature variation through the lens and iris.

Since the cornea determines almost two-thirds of the optical property of the human eye, many researchers have tried to show heat flow in the cornea. This has been due to the exposure of the cornea to heat sources such as laser source and other intense emitters. In this work the main focus was also on the thermal behavior of the cornea.

The overall objective of this study was to capture the possible temperature variation and distribution in the human eye. The model also considers effects of blinking with the convection and radiation in the human eye.

Chapter 2. Human Eye

2.1 Structure of the Eye

The eye is a complex optical system. A relatively small organ in the human body, the eye is a passageway to understanding and emotion. Not only does the eye allows us to see and interpret the shapes, colors, and dimensions of objects in the world by processing the light they reflect or emit, but it also enables us to see and interpret unspoken words and unexplainable environments. A human eye works in a specific bond of the electromagnetic spectrum, and can work over almost, but cannot see objects when light is absent. It acts as a transducer as it changes light rays into electrical signals and transmits them to the brain, which interprets these electrical signals as visual images.

Protected by the cone-shaped cavity in the skull called the orbit or socket, the eye measures approximately one inch in diameter. The orbit is surrounded by layers of soft, fatty tissue, which protect the eye and enable it to turn easily through the use of six muscles. The eye is a complex organ composed of many small parts, each vital to normal vision. The ability to see clearly depends on how well these parts work together. Some of the more important parts of the human eye are the cornea, lens, iris, pupil, retina, sclera, the vitreous body, ciliary body, and aqueous body Fig (1.1). Some eye structures support the main activity of sight: Some secret and carry fluids (such as tears and blood) to lubricate or nourish the eye. Others are muscles that allow the eye to move. Some protect the eye from injury (such as the lids and the non-visual innervations). Some components are messengers, sending sensory information to the brain (such as the pain-sensing nerves in the cornea and the optic nerve behind the retina. The parts of the eye will be discussed in detail in the next section.

One can explain the optics of how the light travels through the eye components and forms an image on the retina;

Light rays bounce off all objects. If a person is looking at a particular object, such as a tree, light is reflected off the tree to the person's eye and enters the eye through the cornea (clear, transparent portion of the coating that surrounds the eyeball).

Next, light rays pass through an opening in the iris (colored part of the eye), called the pupil. The iris controls the amount of light entering the eye by dilating or constricting the pupil. In bright light, for example, the pupils shrink to the size of a pinhead to prevent too much light from entering. In dim light, the pupil enlarges to allow more light to enter the eye.

Light then reaches the crystalline lens. The lens focuses light rays onto the retina by bending (refracting) them. The cornea does most of the refraction and the crystalline lens fine-tunes the focus. In a healthy eye, the lens can change its shape (accommodate) to provide clear vision at various distances. If an object is close, the ciliary muscles of the eye contract and the lens becomes rounder. To see a distant object, the same muscles relax and the lens flattens.

Behind the lens and in front of the retina is a chamber called the vitreous body, which contains a clear, gelatinous fluid called vitreous humor.

Light rays pass through the vitreous before reaching the retina. The retina lines the back two-thirds of the eye and is responsible for the wide field of vision that most people experience. For clear vision, light rays must focus directly on the retina. When light focuses in front of or behind the retina, the result is blurry vision.

The retina contains millions of specialized photoreceptor cells called rods and cones that convert light rays into electrical signals that transmitted to the brain through the optic nerve. Rods and cones provide the ability to see in dim light and to see in color, respectively.

The macula, located in the center of the retina, is where most of the cone cells are located. The fovea, a small depression in the center of the macula, has the highest concentration of cone cells. The macula is responsible for central vision, seeing color, and distinguishing fine detail. The outer portion (peripheral retina) is the primary location of rod cells and allows for night vision and seeing movement and objects to the side (i.e., peripheral vision).

The optic nerve, located behind the retina, transmits signals from the photoreceptor cells to the brain. Each eye transmits signals of a slightly different image, and the images are inverted. Once they reach the brain, they are corrected and combined into one image. This complex process of analyzing data transmitted through the optic nerve is called visual processing.

The work optic of the eye can be summarized as the following:

Vision begins when light enters the eye through the cornea, a powerful focusing surface. From there, it travels through clear aqueous fluid, and passes through a small aperture called the pupil. As muscles in the iris relax or constrict, the pupil changes size to adjust the amount of light entering the eye. Light rays are focused through the lens, and proceed through a clear jelly-like substance in the center of the eye called vitreous, which gives it form and shape. When light rays finally land on the retina, the part of the eye similar to film in a camera, they form an upside-down image. The retina converts the image into an electrical impulse that travels along the optic nerve to the brain, where it is interpreted as an upright image.

2.2.1 Cornea

The cornea is the transparent, dome-shaped window covering the front of the eye. It is a powerful refracting surface, providing 2/3 of the eye's focusing power. Like the crystal on a watch, it gives us a clear window to look through. The cornea is responsible for focusing light rays to the back of the eye. Cornea is 78% water. (Payrau, 1996)

Because there are no blood vessels in the cornea, it is normally clear and has a shiny surface. The cornea is extremely sensitive - there are more nerve endings in the cornea than anywhere else in the body. The reactions of the cornea are quite important in disease processes. It is vascular and therefore reacts differently from those tissues that have a blood supply. Bowman’s layer has little resistance to any pathologic process because of that it is easily destroyed and never generates. Descemet's membrane, on the other hand, is highly resistant and elastic and may remain in the form of a bulging balloon-like structure, called a "descemetocele," after all the other layers of the cornea are destroyed (Adler's, 1987)

2.2.1.1 The Layers of the Cornea

The adult cornea is only about 0.5 mm thick and is comprised of 5 layers: epithelium, Bowman's membrane, stroma, Descemet's membrane and the endothelium.

- The epithelium is layer of cells that cover the surface of the cornea. The epithelium is about 10% of the total thickness of the cornea. It is only about 5-6 cell layers thick, about 50 μm (Davson, 1990) and quickly regenerates when the cornea is injured. If the injury penetrates more deeply into the cornea, it may leave a scar. Scars leave opaque areas, causing the corneal to lose its clarity and luster.
- Bowman's membrane Fig. (2.1) lies just beneath the epithelium. Because this layer is very tough and difficult to penetrate, it protects the cornea from injury. Bowman's layer is a sheet of transparent collagen 12 μm thick.
- The corneal stroma represents certainly one of the most typical examples of highly specialized connective tissue. Its functional efficiency is transparency. The stroma is the thickest layer and lies just beneath Bowman's, Fig. (2.2). It represents some 90 per cent of the corneal thickness. The stroma consists normally of about 75 per cent of water (values of up to 85 per cent are given in

the literature) (Davson, 1949). It is composed of densely packed collagen fibrils that run parallel to each other. This special organization of the collagen fibrils gives the cornea its clarity.

- Descemet's membrane Fig. (2.1, 2.2) lies between the stroma and the endothelium. The endothelium is just underneath Descemet's and is only one cell layer thick. This layer pumps water from the cornea, keeping it clear. If damaged or disease, these cells will not regenerate. Descemet’s membrane is about 10 μm .

- The corneal endothelium is composed of a single layer of cuboidal cells which function to keeps the cornea dehydrated.

Tiny vessels at the outermost edge of the cornea provide nourishment, along with the aqueous and tear film.

Functionally, the most important elements of the cornea are the substantial propria (stroma) and its two limiting cellular membranes, the epithelium and endothelium; damage to the cells of the two membranes, whether mechanical or by interference with metabolism, causes the stroma to lose its transparency as a result, apparently, of the imbibition of water.

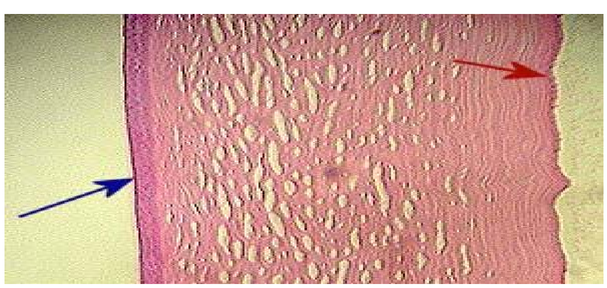

Fig.2.1 Cornea, blue arrow: Outer Epithelium of Cornea (just below Bowman’s Membrane) Red arrow: Descement's Membrane

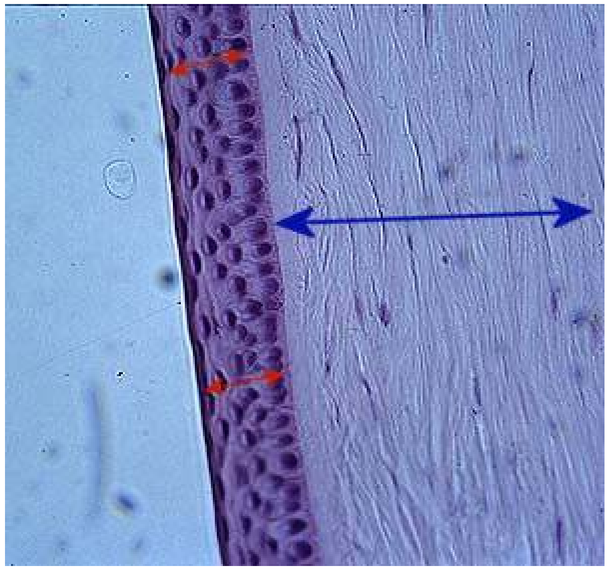

Fig.2.2 Epithelium; blue arrow: Stroma of Cornea; red arrow: epithelium

2.2.2. Sclera

The sclera is commonly known as " The outer wall of the eye." It is the tough, opaque tissue that serves as the eye's protective outer coat. The sclera serves to support and protect the inner contents of the eye. Six muscles connect around the eye to control the movement of the eye. The optic nerve exits through a virtual opening the sclera at the very back of the eye. Sclera contents 68% of water (Payrau, 1996).

In children, the sclera is thinner and more translucent, allowing the underlying tissue to show through and giving it a bluish cast. As we age, the sclera tends to become more yellow.

The sclera becomes transparent when dried. This is assumed to be the result of the concentration of the ground substance so that its refractive index becomes close to that of the collagen. As this happens when the tissue is nearly dry, it acquires a uniform refractive index (Davson, 1962).

The differences between the compositions of the various types of connective tissues, for instance cornea and sclera are more often quantitative than qualitative. The water content of cornea is somewhat higher than that of sclera. The cornea and sclera together form the tough tunic of the eye, which withstands the intra-ocular pressure from within and protects the contents from mechanical injury from without.

2.2.3 Iris

The pigmented tissue, which rests behind the cornea and in front of the natural lens. This is the part of the eye that gives it color (i.e. blue, green, brown). The opening in the center of the iris is the pupil. The iris acts like a camera shutter and controls the amount of light that enters the eye. The iris behaves as a diaphragm, modifying the amount of light entering the eye.

On meridional section the tissue of the iris consists of two main layers, or laminae, separated by a much less dense zone (the cleft of Fuchs). The posterior lamina contains the muscles of the iris, and is covered posteriorly by two layers of densely pigmented cells, the innermost (nearest the aqueous humour) being the posterior epithelium of the iris, which is continuous with the inner layer of the ciliary epithelium Fig. (2.3).

Altogether the iris does not potent sufficient stiffness or rigidity to determine the position and shape of the whole membrane. In the normal eye a fair portion of the iris rests upon the crystalline lens. Therefore, the size and position of the lens determines to a large extent the position and shape of the iris (Davson, 1962).

The sphincter muscle lies around the very edge of the pupil. In bright light, the sphincter contracts, causing the pupil to constrict. The dilator muscle runs radially through the iris, like spokes on a wheel. This muscle dilates the eye in dim lighting.

The iris is flat and divides the front of the eye (anterior chamber) from the back of the eye (posterior chamber). Its color comes from microscopic pigment cells called melanin. The color, texture, and patterns of each person's iris are as unique as a fingerprint.

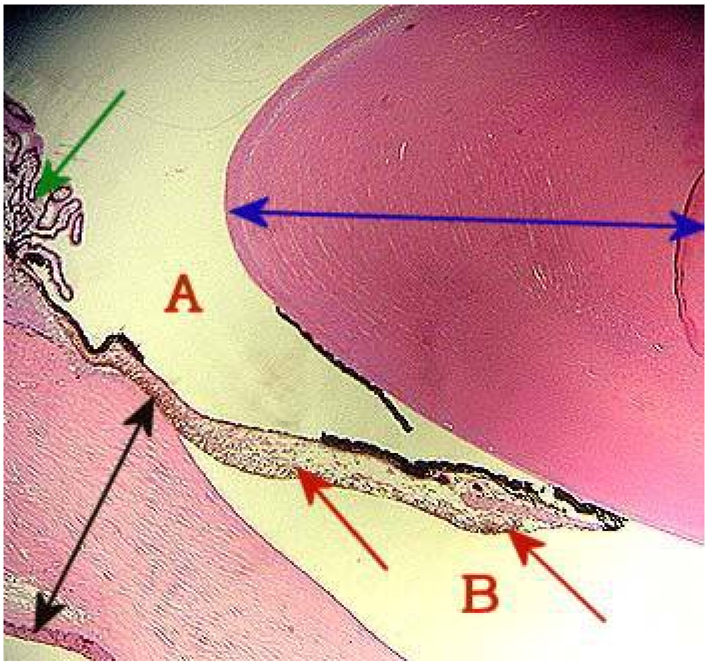

Fig. 2.3 Blue arrow:Lens; Red arrow: Iris; Green arrow Ciliary Body; Black arrow Cornea; A: Posterior Chamber; B: Anterior Chamber

2.2.4 Lens

The crystalline lens is located just behind the iris Fig. (2.3). The purpose is to focus light onto the retina. The nucleus, the innermost part of the lens, is surrounded by softer material called the cortex. The lens is encased in a capsular-like bag and suspended within the eye by tiny "guy wires" called zonules. The lens contains 65 per cent of water. The percentage of the water decreases with aging (Davson, 1949).

In young people, the lens changes shape to adjust for close or distance vision. This is called accommodation, but with age the lens gradually hardens, diminishing the ability to accommodate.

Accommodation is a procedure that changes the focusing distance of the lens. The lens thickens, increasing its ability to focus at near. A young person's ability to accommodate allows him or her to see clearly far away and up close. At about the age of 40, the lens becomes less flexible and accommodation is gradually lost, making close-range work increasingly difficult. This is known as presbyopia.

Because the lens is separated from the surrounding aqueous chamber by the capsule posteriorly and by the epithelium capsule anteriorly, any damage to the capsule results in occurrence of the cataracts.

2.2.5 Pupil

The pupil is the opening formed by iris. It functions like the diaphragm in a camera, controlling the amount of light that enters the eye. The pupil is small in bright light and large in dim light. The size of the pupil varies with age (Adler's 1987).

People commonly think of their pupil as merely the black circle in the middle of your eye. However, pupil serves an important purpose as the doorway in the iris that is responsible for expanding and contracting to modulating the amount of light entering the back of the eye.

2.2.6 Ciliary Body

Located just behind the iris, the ciliary body is instrumental in controlling focusing of the eye and the production of aqueous fluid. The ciliary processes are responsible for the production of aqueous humor. The ciliary body is a well-vascularized tissue with a relatively high rate of blood flow (Caprioli, 1984).

2.2.7 Retina

The retina is a multi-layered sensory tissue that lines the back of the eye. It contains millions of photoreceptors that capture light rays and convert them into electrical impulses. These impulses travel along the optic nerve to the brain where they are turned into images.

There are two types of photoreceptors in the retina: rods and cones. The retina contains approximately 6 million cones. The cones are contained in the macula, the portion of the retina responsible for central vision. They are most densely packed within the fovea, the very center portion of the macula. Cones function best in bright light and allow us to appreciate color.

There are approximately 125 million rods. They are spread throughout the peripheral retina and function best in dim lighting. The rods are responsible for peripheral and night vision.

2.2.8 Aqueous Humour

The aqueous is the thin, watery fluid that fills the space between the cornea and the iris (anterior chamber). It is continually secreted by the ciliary body, the part of the eye that lies just behind the iris. This fluid nourishes the cornea and the lens and gives the front of the eye its form and shape. It is now accepted that active transport of certain solutes by the ciliary epithelium is the most important factor in aqueous humor formation. The amount of the aqueous secreted depends on the rate of active solute transport by the ciliary epithelium (Adler's, 1987).

Solute exhanges between the aqueous and the cornea are necessary for normal corneal metabolism (except oxygen,since it is largely supplied by the atmosphere).

2.2.9 Vitreous Humour

Behind the lens and in front of the retina is a chamber called the vitreous body, which contains a clear, gelatinous fluid called vitreous humour**.** The vitreous is a thick, transparent substance that fills the center of the eye. It is composed mainly of water and comprises about 2/3 of the eye's volume, giving it form and shape. The viscous properties of the vitreous allow the eye to return to its normal shape if compressed. The vitreous humour retains the retina in position and prevents rapid spread of large molecules or cells, while allows small nutrient molecules to move. As it was mentioned above, about 99 per cent of the vitreous humor's wet weight is water but because of the proteins that within it, it becomes a viscous fluid.

In children, the vitreous has a consistency similar to an egg white. With age it gradually thins and becomes more liquid. The vitreous is firmly attached to certain areas of the retina. As the vitreous thins, it separates from the retina, often causing floaters.

These tissues are all critical components of the eye and one could see from the function of the each part, each has a different mechanism of action so that the eye can function as a system.

It is considered and assumed that any internal or external temperature change in the eye can affect the cellular mechanisms of the eye. Temperature changes can affect tissues in several ways; it can kill cells, denature proteins causing a loss of vision, temperature can slow down or up the metabolism of cells and be involved in pathological changes of the eye (Zeiss, 1930; Huber, 1960; Gros, Bronner, and Vrousos, 1967). Therefore, it is important to understand the effect of a temperature changes as overall.

Since the eye is one of the vital parts of the human eye and knowing that without a good vision or having a problem in the vision prevents or gives a big difficulty for a person to be able to do works that are depend on and related to the eye directly or indirectly, it is worthy to analyze the human eye that is subjected to a temperature change in it or around ambient temperature of it.

Chapter 3. Theoretical Formulation

3.1 Introduction

To simulate the heat distribution of the eye an advanced finite element program, ABAQUS was used. The geometric parameter of the eye was obtained from numerous literature sources. The eye is assumed to be an axisymmetric, deformable, solid body. The components of the eye were drawn separately and they were merged by using interaction property so that the heat between any two components of the eye can distribute in a smooth fashion. The eye was considered to have six major components: Cornea, intermediate (the area between cornea and sclera), sclera, iris, lens and inner part (vitreous humor and aqueous humor), Fig. (1.1). The reason to have a separate part as intermediate was due to small part sclera exposed to the environment and therefore the boundary conditions are considered to be the same as those of the cornea. The vitreous humor and aqueous humor were considered one part since their material properties are very similar. All the parts were meshed separately which helped to mesh some areas denser than other areas. Between the two parts of the eye a thermal surface interaction was used. These interactive surfaces include gap conductance. This provides conductive heat transfer between closely adjacent (or contacting) surfaces. Thermal interaction involves convective heat flow across the boundary layer between solid surfaces. The conductive heat transfer among the contact surfaces is assumed to be defined by

$$q = k(\theta_A - \theta_B)$$

Where q is the heat flux per unit area crossing the interface from point **A** on one surface to point **B** on the other. θ_A and θ_B are the temperatures of the points on the surfaces, and **k** is the gap conductance. Point **A** is a node on the slave surface; and point **B** is the location on the master surface contacting the slave node or, if the surfaces are not in contact, the location on the master surface with a surface normal intersects the slave node. The gap conductance k is defined as

$$k = (\bar{\theta}, d, p, \bar{f}_\gamma, \overline{|\dot{m}|}),$$

where

$\bar{\theta} = \frac{1}{2}(\theta_A + \theta_B)$ is the average of the surface temperatures at A and B,

d is the clearance between A and B,

p is the contact pressure transmitted across the interface between A and B

$\bar{f}_\gamma = \frac{1}{2}(f_\gamma^A + f_\gamma^B)$ is the average of any predefined field variables at A and B,

and

$\overline{|\dot{m}|} = \frac{1}{2}(|\dot{m}|_A + |\dot{m}|_B)$ is the average of the magnitudes of the mass flow rates per unit area of the contact surfaces at A and B.

It is assumed that the eye remains open for about 8 seconds, and afterwards the eye is assumed to be closed 0.5 seconds. When the eye is open (8 sec) both convection and radiation effects are considered. In the case of the closed of the eye only the convection factor is considered. Eight-node (8-node) quadratic axisymmetric heat transfer quadrilateral elements are used. The time is linearly extrapolated. Time integration in transient heat problems is done with the backward Euler method (sometimes also referred to as the modified Crank-Nicholson operator) in the pure conduction elements. This method is unconditionally stable for linear problems. A fixed increment is used for the time so that the intended time can be obtained. Fixed time increments equal to the initial time increment given on the data line will then be used throughout the analyses. In transient heat transfer analysis with second-order elements there is a relationship between the minimum usable time increment and the element size.

$$\Delta t > \frac{\rho c}{6k} \Delta l^2$$

where Δt is the time increment, ρ is the density, c is the specific heat, k is the thermal conductivity, and Δl is a typical element dimension (such as the length of a side of an element).

In the program uncoupled heat transfer analysis is considered which means the heat transfer problem involves in conduction, and boundary radiation. In this heat transfer analysis the temperature field is calculated without knowledge of the stress/deformation state or the electrical field in the bodies.

Table 3.1. Characteristics of the Eye Components

	Node#	Element#	Element Type
Cornea	1941	600	8-node quadratic
Iris	1916	581	8-node quadratic
Lens	981	300	8-node quadratic
Sclera	5128	1505	8-node quadratic
Inter	11529	3658	8-node quadratic

Table 3.2. Material Properties of the Eye

	Thermal Conductivity $Cal/sec.mm.C^{o}$	Specific Heat $Cal/gram.C^{o}$	Density $gram/mm^{3}$	Reference
Cornea	8.36e-05	0.87	1.062e-03	LSU Eye Center
Aqueous	1.3805e-04	0.9984	9.96e-04	LSU Eye Center
Sclera	2.4e-04	0.76	1.1e-03	LSU Eye Center
Lens	9.55e-05	0.717	1e-03	Tissue,Neelakan Taswany and Ramakrishnan 1979
Iris	2.4e-04	0.76	1.1e-03	Accepted to be As Sclera
Vitreous	1.3805e-04	0.9984	9.96e-04	Accepted to be as Aqueous
Water	1.47e-04	1	1e-03	
Air	5.7e-06	0.24	1.165e-06	

Specific heat is defined as

$$c(\theta)=\frac{dU(\theta)}{d\theta},$$

where $U(\theta)$ is the internal energy due to thermal effects only. This relationship is usually written in terms of a specific heat, neglecting coupling between mechanical and thermal problems.

3.2 Heat Transfer

3.2.1 Introduction To The Heat Transfer

Heat transfer is energy transfer due to temperature differences. It can be classified as conduction, radiation and convection. Conduction and convection require a material medium. The energy flux across a surface at any location can be found from a knowledge of the state of the medium in the immediate vicinity of the location, and the effect of the disturbance of the temperature is propagated much more slowly than in radiation. In radiative heat transfer the energy transport does not require a material medium, and to determine the energy flux at a point, one needs to know the state of all regions that the point sees. Heat transfer is a surface phenomenon.

Heat transfer is the transfer of Heat energy due to temperature difference.

- Heat transfer (HT) supplements the first and second laws of thermodynamics that deal with equilibrium phenomena. HT gives information on the "rate" of thermal energy transport.

• HT is central to numerous engineering and scientific problems.

There are many examples for the heat transfer, some of them are: Pasteurizing milk, energy lost from a house by conduction through a window, solar heating of the earth, and air conditionings.

3.2.2 Energy Balance

The energy balance is (Green and Naghdi)

$$\int_V \rho \dot{U} dv = \int_S q dS + \int_V r dV,$$

where V is a volume of solid material, with surface area S **;** ρ is the density of the material; $\dot{U}$ is the material rate of the internal energy; q is the heat flux per unit area of the body, flowing into the body; and r is the heat supplied externally into the body per unit volume.

3.2.3 Conduction

Conduction is the transfer of heat across a medium from a source of higher temperature to a source of lower temperature. It results from the physical contact of one body with another. The conduction of heat energy will always occur from a region of greater temperature to a region of lower temperature until both region temperatures reach a state of thermal equilibrium. An example would be when a cooking pot is placed on the solid surface of a hot stove. When the pot comes in direct contact with the stove element, heat is transferred to the pot by means of the movement of molecules (kinetic energy). Conduction is a very effective method of heat transfer in metals, but gases conduct heat poorly in comparison. Nevertheless, when earth surfaces become heated by radiation, the air above those surfaces becomes heated by conduction from them. Have you ever left a metal spoon in a pot of soup being heated on a stove? If you left it for some time, you noticed that the handle of the spoon was hot when you returned. Perhaps you wondered how the handle became so hot. It is because of the heat conduction.

Heat conduction is assumed to be governed by the Fourier law,

$$f = -k\frac{\partial\theta}{\partial x},$$

where k is the conductivity matrix, $k = k(\theta)$; f is the heat flux; and x is position.

3.2.4 Convection

Convection is the transfer of heat by the movement of air. Hot air masses tend to rise and are replaced by surrounding cooler, denser air. These movements of air masses can be small in a certain region, or large cycles in the troposphere, covering large sections of the earth. Convection in heat transfer is a process, which involves the diffusion of heat and the advection of energy by flow. Convection is described as the process by which heat is transferred by the movement of a heated fluid. The fluid through which heat moves may be either gases, such as air, or a liquid, such as water.

Three types of convection may be observed:

- natural convection
- forced convection and

- atmospheric convection

Natural convection depends on the tendency of most fluids to expand when heated and thus undergo a decrease in density. As a result, the warmer, less dense portion of the fluid will tend to rise through the surrounding cooler fluid. If heat is continuously being supplied, the cooler fluid that flowed in to replace the rising warmer fluid will warm up and also rise. Thus a current, a convection current, becomes established. This convection current is due solely to the non-uniformity of fluid temperature.

Circulation caused by natural convection accounts for the uniform heating of water in a kettle: the heated molecules expand the space they move in through increased speed against one another, rise, and then cool coming closer together once again.

Forced circulation involves the transport of fluid by methods other than that resulting from variation of density with temperature. Examples of forced convection are the movement of air by a fan or of water by a pump.

Atmospheric convection produces currents, which are created by local heating effects such as solar radiation (which causes air to be heated and rise), or contact with cold surface masses (which cause air to cool and sink). Such convection currents determine the movement of large air masses above the Earth, the action of the winds, rainfall as well as ocean currents.

Convection can be described as the following:

$$q = h(\theta - \theta^0)$$

where h = h (x, t) is the film coefficient and

$\theta^0 = \theta^0(x,t)$ is the sink temperature.

3.2.5 Radiation

Basically, radiation is the movement of energetic particles or waves through space. These waves or particles can share their energy with (and sometimes damage) materials like human tissue. Radiation is generated by common sources like the sun, radioactive materials, and electronic devices. Thermal radiation is energy emitted by matter that is at a finite temperature. Emission occurs not only from solids, but also from gases and liquids. By looking at some real examples in the real life, it would help us to understand heat radiation better; If you have stood in front of a fireplace or near a campfire, you have felt the heat transfer known as radiation. The side of you nearest the fire became warm, while your other side remained unaffected by the heat. Although you are surrounded by air, the air has nothing to do with this transfer of heat, which is known as radiation.

Radiation is the transfer of heat through space by means of wave energy. Most of the wave energy that comes to the earth from the sun is in the form of visible light, which is really not white as it appears to us. Rather it made of waves of different energies that are separated in rainbows into what our brains interpret as colors, including red, orange, yellow, green, blue, indigo and violet. Waves from the sun, which we cannot see, are infrared, which has less energy than red, and ultraviolet, which has more energy than violet light.

Heat radiation can be described as the following;

$$q = A\left((\theta - \theta^Z)^4 - (\theta^0 - \theta^Z)^4\right),$$

where is A is the radiation constant (emissivity times the Stefan-Boltzman constant) and θ^Z is the absolute zero on the temperature scale used.

Where Stefan-Boltzman constant is, σ, $5.670400 \text{x} 10^{-8}$ W/m^2. K4

Nature requires that, at a given temperature, a body will emit a unique distribution of energy in wavelength. Thus when you heat a poker in the fire, it first glows a dull red-emitting most of its energy at a long wavelengths and just a little bit in the visible regime. When it is white-hot the energy distribution has been both greatly increased and shifted towards the shorter-wavelength visible range. At each temperature, a black body yields the highest value of the emissivity that the body can attain (John H.Lienhard IV, V)

3.2.6 Boundary Conditions

Boundary conditions can be specified as prescribed temperature, $\theta = \theta(x, t)$; prescribed surface heat flux, q = q (x, t) per area; prescribed volumetric heat flux,q = (r, t) per volume; surface convection: $q = h(\theta - \theta^0)$, where h = h (x, t) is the film coefficient and $\theta^0 = \theta^0(x, t)$ is the sink temperature.; and radiation: $q = A\left((\theta - \theta^Z)^4 - (\theta^0 - \theta^Z)^4\right)$, where is A is the radiation constant (emissivity times the Stefan-Boltzman constant) and θ^Z is the absolute zero on the temperature scale used.

Chapter 4. Analysis of the Human Eye Model

4.1 Introduction

A finite element program, ABAQUS, was used to simulate the temperature distribution through the human eye including the effect of eye-blinks. ABAQUS is an advance finite element model used in many different areas of engineering. Nowadays, the finite element method is used to simulate behavior of different materials. ABAQUS is one of most often-used finite element program both in academic and industry. In this work ABAQUS, based on the finite element method, was used to simulate heat transfer in the human eye. The human eye model was created using ABAQUS and calculations were done using ABAQUS.

4.2 Creating the Model For the Human Eye

To simulate the eye, first, the eye's components (cornea, iris, lens, sclera) properties such as radius, thickness and their material properties were obtained. Each of the eye components was drawn separately Fig. (4.2.3, 4.2.4,4.2.5,4.2.6,4.2.7,4.2.8) and each material property of the eye components was assigned appropriately (table 2). Then all the components were assembled Fig. (4.2.1). The assembling process took some time. The reason for it was the difficulty of obtaining the exact parameters of the eye and then to assemble them to make them similar overall to a real human eye. The other problem that was faced during the drawing geometry and assembling the eye components was the generation and regeneration of eye geometry using ABAQUS.

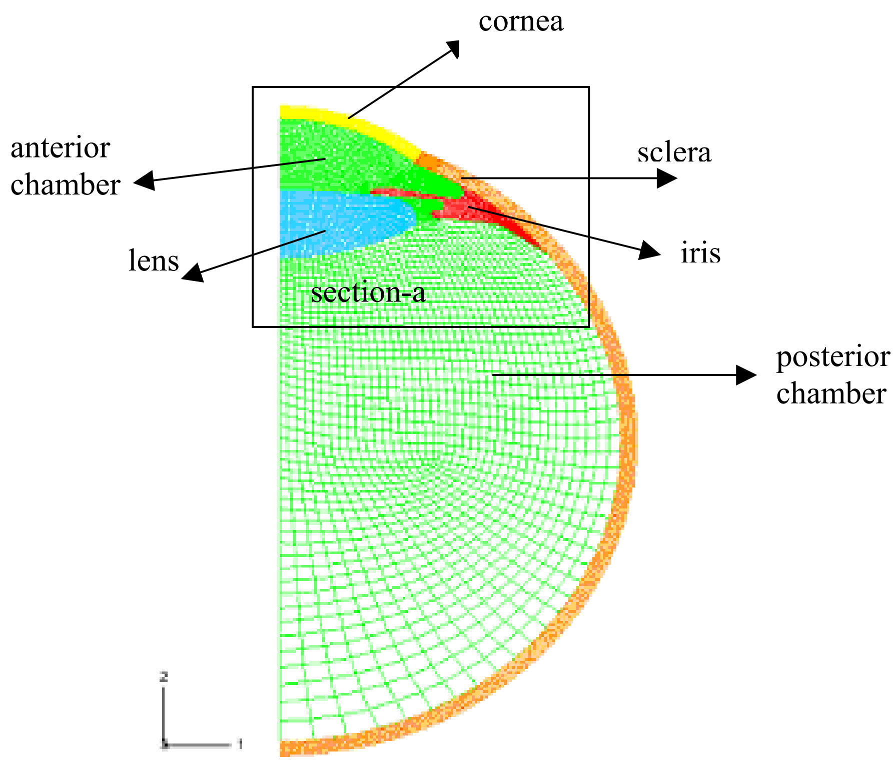

Fig.4.2.1 Eye

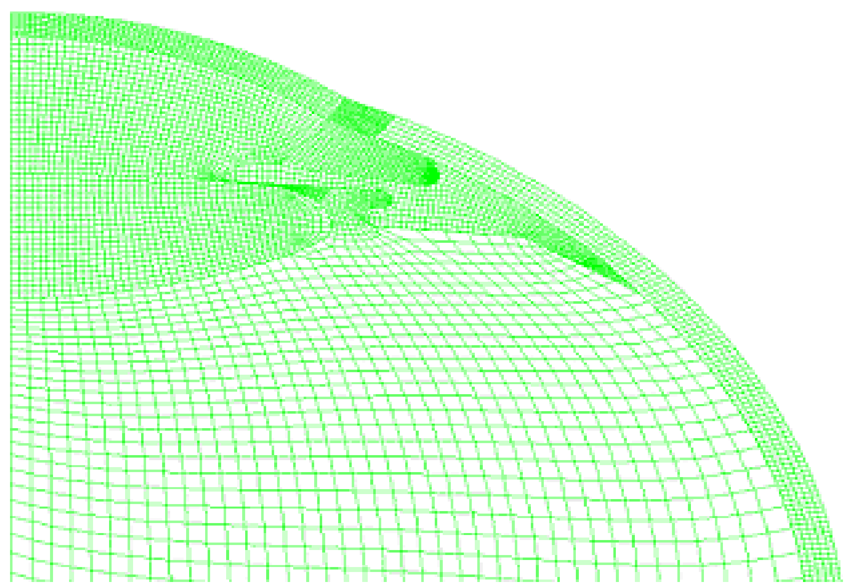

Fig.4.2.2 Cross-section of the eye (section-a)

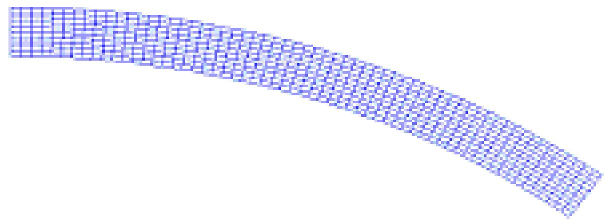

Fig. 4.2.3 Cornea-meshed

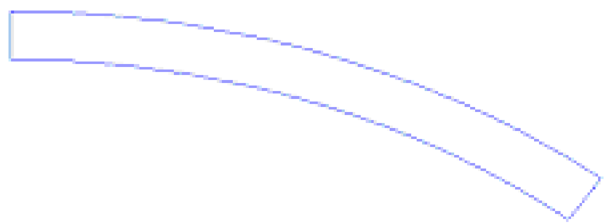

Fig. 4.2.4 Cornea

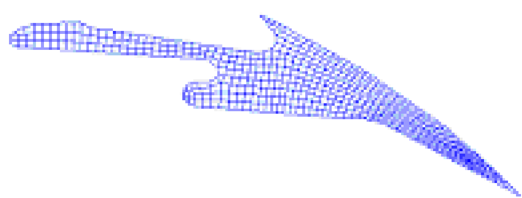

Fig. 4.2.5 Iris-meshed

Fig. 4.2.6 Iris

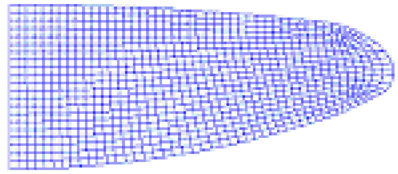

Fig 4.2.7.Lens-meshed

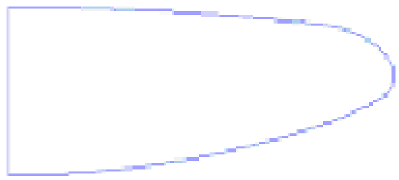

Fig 4.2.8.Lens

The reason for it was the lack of capability of drawing a complicated figure in ABAQUS. This problem was solved by drawing the eye components again and again, which took enormous time. The geometry of the eye could be drawn first in different software such as AutoCAD but the problem that appeared using AutoCAD and then transferring the file to Abaqus was also the difficulty of assembling the components. After assembling the eye components was to create the step in the step mode. Each step here means time in another words every step has own time so that the required time conditions could be created. Two main steps were required which were: all the odd steps (1,3,5,7…63) corresponding to the eye opening and the even steps (2,4,6,8…64) corresponding to eye closure. By applying these two steps, opening and closing the eye, to simulate blinking, consequent heat transfer through the components was simulated. In this work, the odd numbers of steps (step-1, step-3…. step-63) correspond to 8 seconds, which was adopted the average time for opening of the human eye and the even numbers of steps (step-2, step-4…. step-64) correspond to 0.5 seconds, which was adopted the average time of closure of the eye.

After the step mode, was created the interaction in between the eye components. This had to be done since each of the eye components has different conductivity, specific heat and density; some of the components such as anterior chamber and posterior chamber have close material parameters. To make more understandable the interaction property was applied, one can consider cornea; and close to the cornea are sclera Figs. (1.1,4.2.1). Therefore, three interactions were created between these three components of the eye; cornea-sclera interaction, cornea-anterior chamber interaction, and the sclera-anterior interaction. The interactions between the other parts of the eye were created with the same logic.

4.2.1 Boundary Conditions for the Eye Model and Meshing of the Eye Model.

In this model the eye is subjected to the three Temperature Boundary Conditions (TBC). The first TBC was the initial condition, which was assumed to be $37\,C^{o}$ over all the eye components this represents the eye being closed for an extended time. The other two TBC were set on the exterior side of the cornea and the white part of the eye, known as sclera. These two temperature boundary conditions are convection and radiation. In the convection the temperature was assumed to be $37\,C^{o}$ and for the radiation the temperature was set to be $0\ C^{o}$. During the opening of the eye, it was assumed that both convection and radiation occur at the cornea and a small part of the sclera. Therefore, in the case of eye opening, it was assumed that the eye has radiation and convection and since that this boundary condition was set on the even odd step, as it was mentioned before the odd steps (step-1, step-3…step-63) are corresponding the opening time of the human eye. In the case of eye closure, it was assumed that only convection appear on the boundaries and again since this boundary was applied for the eye closure, this means that this TBC was applied for the even steps (step-2, step-4…step-64) as it was mentioned previously.

The mesh of the eye was done for each of the eye components separately Figs. (4.2.3, 4.2.5, 4.2.7); this allowed the desired mesh to control the areas that were being investigated for the temperature distribution in these particular areas. Therefore cornea, iris, lens, anterior chamber were meshed denser than other components of the eye, this was done to able to capture any small changes in the temperature variation and to be more precise to its location. An 8-node quadratic axisymmetric heat transfer quadrilateral element was used. It should be noted that since each component of the eye was meshed separately, the compatibility between meshes had to be set so one could have a problem between one boundary of the eye component and the adjacent boundary of another eye component in meshed cases. Since the model was calculated on a SGI lynx machine, there was no problem to increase the density of the mesh of any eye component.

After all these steps were done, the eye component parameters, assembling, interactions between components, time and boundary conditions and certain meshed were done and applied, the creation and design of the desired human eye model was completed and the job for the model was ready to run. The job ran many times with different conditions and changing the eye components parameters so that to be able to see the response of the eye components and how it differs the temperature through them. Running the job and trying to analyze them took an enormous time. The response of the eye to the different material parameters did not affect the cornea temperature generally, but it should be noted that one could expect the effect of the changing anterior chamber parameters may have an influence on the cornea temperature. This was observed, as it was mentioned previously, by running the job for the eye model for different conditions many times and repeat them. One of the jobs that was run to be sure that the model gives the correct result in another words to be confident that the eye model works properly the water parameters (specific heat, density, conductivity) were applied to the eye components.

The reason why the water parameters were used was the close material properties of the eye to the water properties. The result of this test was very close to the result of the eye model with the real parameters. Moreover, to verify the eye model the eye components properties that were used by (Scott[1] 1988) was applied and compared with her result although in her model some of boundary conditions that was used in that model may differ from this present eye model. The result showed similarity to the present eye model with the own material properties. Initially it was noted that the temperature various more often through the eye components, but after some time 187 seconds or approximately 3.12 minutes the temperature through in the eye components began to stabilize. The difference in the temperature between the cornea anterior part and cornea posterior part after 4.53 minutes was around 0.1 C^o.

Closure and opening of the eyelids show different variation of temperature. The temperature rises for 1.5 C^o when the eyelids are open and decreases to 1.1C^o when the eyelids are closed (Mapstone, 1968). When the eyelids are open cornea surface temperature is affected because of convection and radiation It should be also noted that the difference between the peak of the anterior part of the cornea and the adjacent side to the sclera is approximately 0.25 C^o. This difference may be explained by considering that since the cornea is adjacent to the sclera and the two temperature boundaries vary, this kind of temperature difference occur. The difference 0.15 C^o may have a negative effect on the eye as a pain in the cornea (Beuerman, 1979). From the Fig. (5.40) it can be seen that the temperature in the anterior part of the cornea and posterior part of the cornea is decreasing by the time. And the same behavior of the eye can be seen from the experimental result that was conducted by (Tanelian 1984). The heat loss of the cornea is more on the peak of the cornea then adjacent side to the sclera this heat loss recorded after 4.53 seconds. By comparison this heat loss with the heat loss on the peak of the cornea at 8 seconds, it is seen that at 8 seconds, during the opening of the eye, the heat loss is less across the anterior surface of the cornea then at 8 seconds. Again, this kind of heat loss occurs because of the different boundary conditions between cornea and sclera. Light can be a potential damaging effect on the corneal epithelium (Jordan, 1986). The sunlight exposure may have an influent in the appearing of the ocular disease (Shiyoung 1994). The surface temperature of the cornea was measured using bolometer (Mapstone, 1968); the mean temperature variation on the cornea surface was obtained to be 0.8 C^o under 33.2-36 C^o.

The temperature difference between anterior part of the lens and posterior surface of the lens is approximately $0.19\,C^o$ at 4.53 minutes Figs. (5.10, 5.40). It was observed that the temperature changes appear mainly in the anterior surface of the lens, this verifies the common thought that the temperature in the core of the human eye does not change. The thermal behavior of the eye is important for the occurrence of the cataracts. It was recognition of the frequent development of cataracts to occur among glass workers since the effect of heat on the human lens. The exposure to sunlight or high ambient temperature has an influence on the thermal behavior of the lens and which would be the reason for cataracts occurrence (Abdulrahman A., 1986). From the comparison in the temperature difference between anterior surface of the cornea and posterior surface of the lens at the time 4.53 minutes, it can be seen to be approximately 0.372 C^o and the temperature difference between posterior surface of the cornea and anterior surface lens is around $0.152\,C^o$ Fig. (5.40). All these comparisons in the eye components can help to understand the thermal behavior of the eye.

The temperature vs. time variation across the thickness of the cornea for the given nodes was analyzed. It was obvious that with the increasing of the time the temperature across the cornea thickness is dropping and after some time it becomes steady. And the same behavior was also observed for the lens. The comparison in the difference in the thermal behavior of these main parts of the eye can be observed for the same time. In this present model, it can be also seen the thermal behavior of the anterior chamber, posterior chamber and the comparison between anterior chamber-posterior chamber, anterior chamber-cornea, anterior-lens. The overall thermal behavior of the eye is seen at Fig. (5.64). From the Fig. (5.64) observed that thermal behavior and change in the temperature of the eye components are close to each other.

Chapter 5. Results and Conclusion

In this work a human eye model was created to simulate the thermal behavior of the eye using the ABAQUS software, which is based on the finite element method. In this model the temperature distribution in the human eye was obtained by using certain prescribed thermal boundary conditions and appropriate material properties in order to study the eye blinking effect. The model results were compared with experimental results. The overall behavior of the eye is observed for 4.53 minutes in Fig. (5.64). This study may help understand the thermal behavior of the eye, which can be very crucial in ocular diseases that cause pain in the cornea. It also may help to understand the occurrence of the cataracts in the lens, and interactions between the different eye components using computerized simulation. Such models may prove to be invaluable in eye therapy and surgery.

The difference in the cornea front surface temperature and cornea back surface temperature was around $5\,C^o$ and this was obtained in 10 seconds Fig. (5.67, 5.68, 5.69). The experimental results (Tanelian and Beuerman, 1979) indicated that the temperature difference between front and back cornea is 5.5 C^o Fig. (5.70). The temperature that obtained from the present model shows a good agreement with the experimental results. Nevertheless, it should be noted that there might be a problem in the experiment; because, when the temperature at the front surface of the cornea was increased to some prescribed temperature, it took just 2 seconds for the temperature to reach the back surface of the cornea. In this model, it was seen that this is almost impossible since there is a cooling effect inside the aqueous humor due to the convection in the aqueous humor which normally would delay or prevent the temperature in the back of the cornea surface to be heated in a such short time of 2 seconds and reach at the same scale of temperature as the front surface of the cornea. Another reason that could explain why the temperature from the front surface of the cornea to the back surface of the cornea reached in short time (2 seconds) is perhaps the boundary conditions that were prescribed in the experiments. However, the results from the present model when compared to the experimental result are quite promising. In order to obtain better correlation with experimental results and understanding a new set of experiments need to be conducted with different boundary conditions and simulate the same conditions using the present model with considering the same boundary conditions and perhaps by also refinement of the present model.

The accuracy of the solution and model depends on the ability of the model to accurately predict the heat flow in the different eye components and the different heat conductivity coefficients in the eye components. One needs to incorporate more details such regarding effects that may have influence on the eye temperature such as ciliary body, blood flow etc. Drawbacks of the current simulation process are the inability to apply to the current software conditions and parameters that may have effect on the human eye, the complication of the eye mechanism itself, not being able to conduct an experiment to a human eye directly and as consequence of it, not having enough information of the eye work mechanism and certainly the speed of limitations of the processors. The eye was subjected to temperature changes for 272 seconds (approximately 4.53 minutes). To be able to set up more conditions and increase the time simulation one certainly needs to have a super computer. Overall, this present human eye model can be considered as an upgraded theoretical model and can lead to further investigation for the temperature distribution through the human eye.

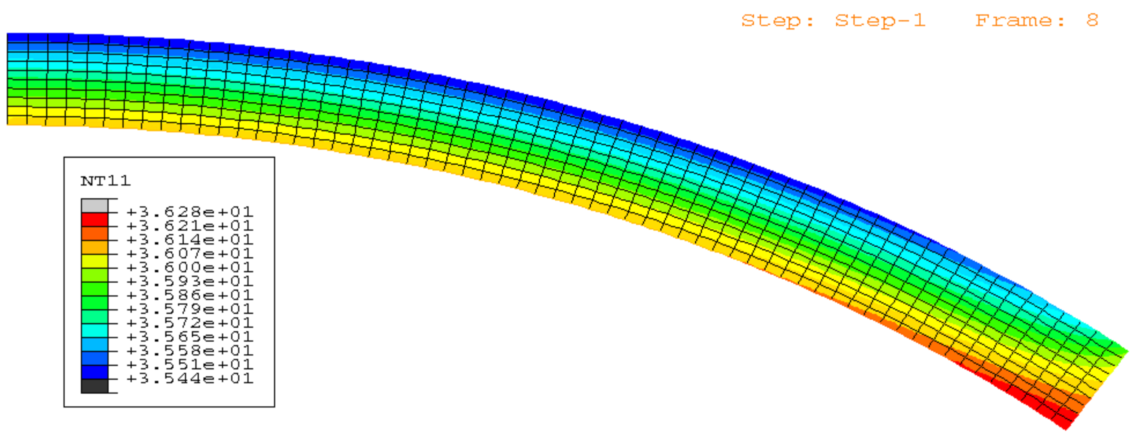

Fig.5.1 Cornea Temperature distribution (8 sec)

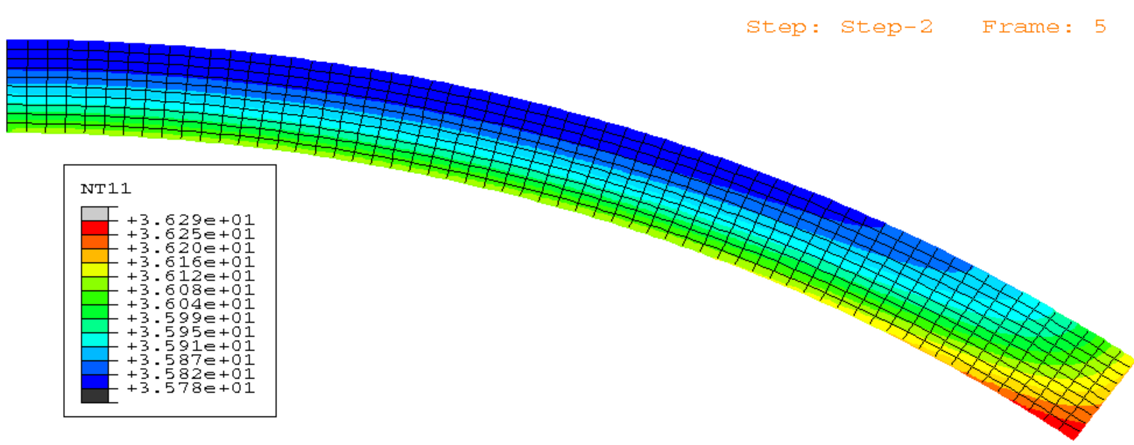

Fig.5.2 Cornea Temperature distribution (8.5 sec)

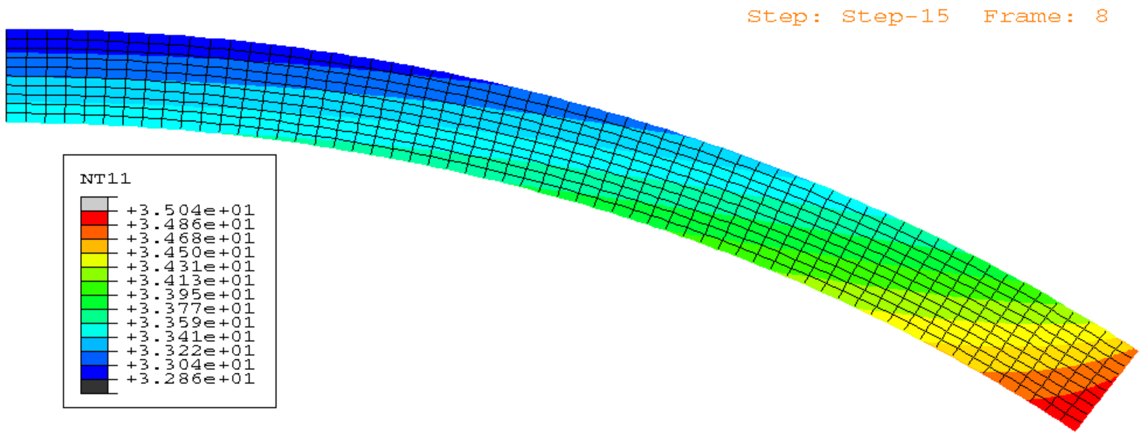

Fig.5.3 Cornea Temperature distribution (67.5 sec)

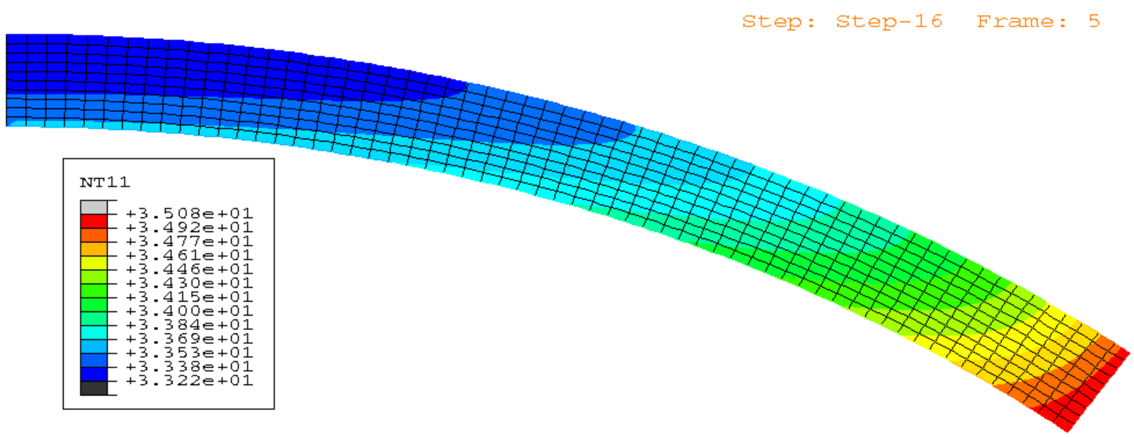

Fig.5.4 Cornea Temperature distribution (68 sec)

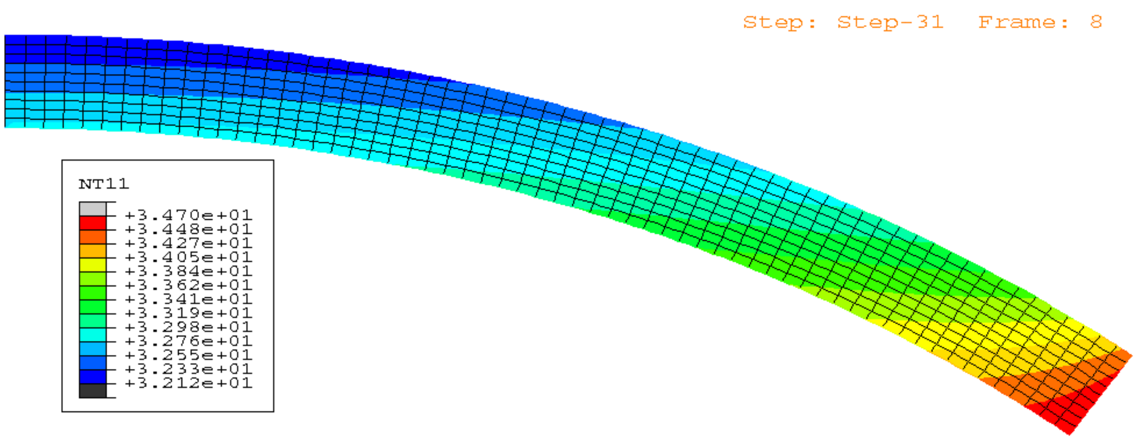

Fig.5.5 Cornea Temperature distribution (135.5 sec)

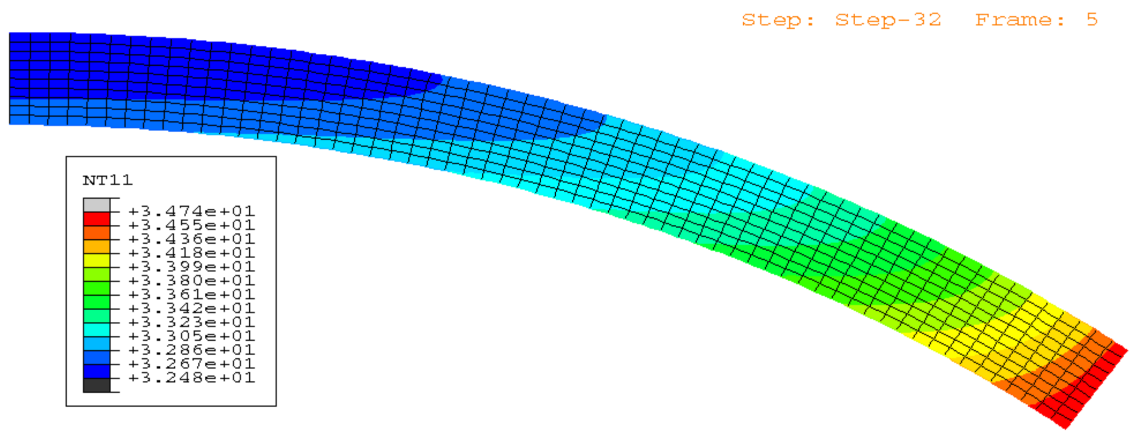

Fig.5.6 Cornea Temperature distribution (136 sec)

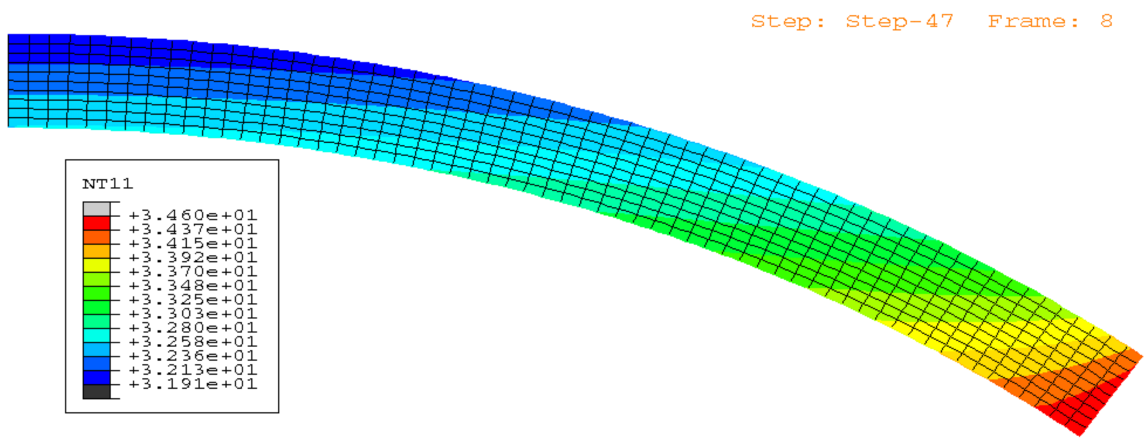

Fig.5.7 Cornea Temperature distribution (203.5 sec)

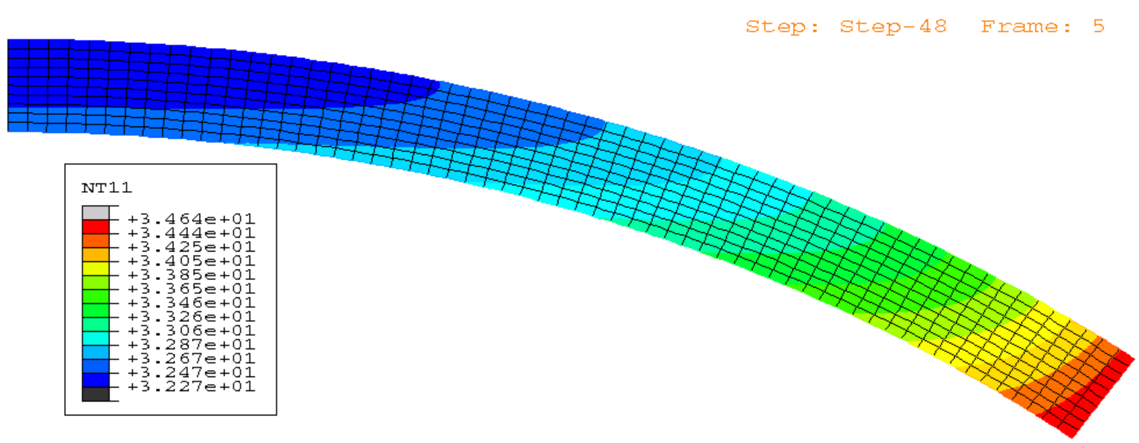

Fig.5.8 Cornea Temperature distribution (204 sec)

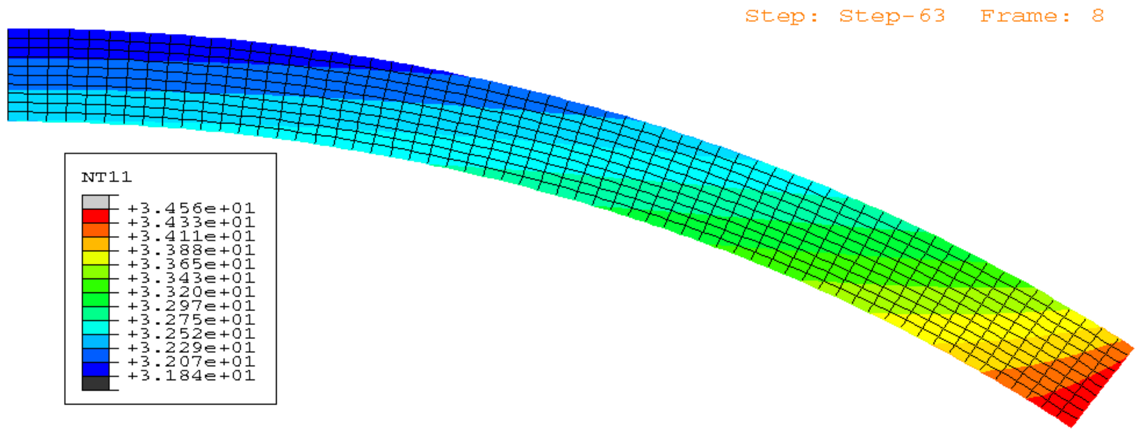

Fig.5.9 Cornea Temperature distribution (271.5 sec)

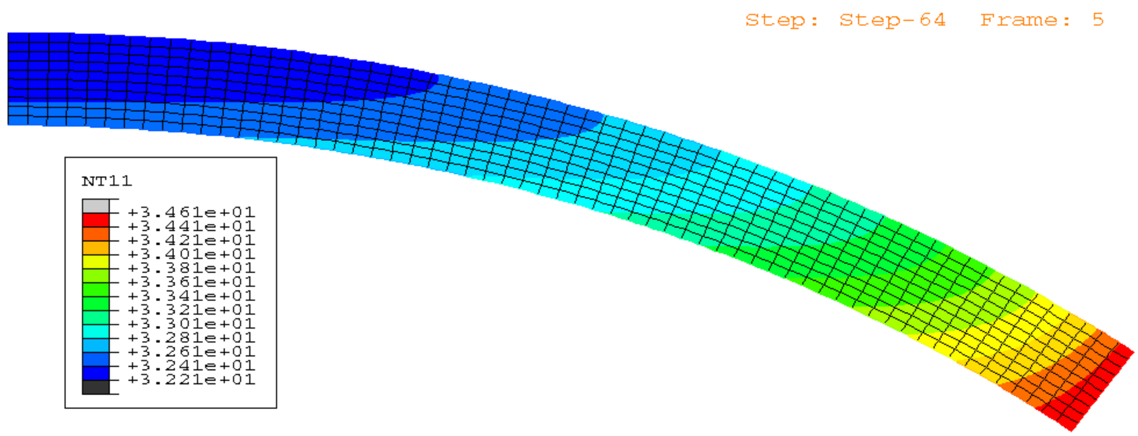

Fig.5.10 Cornea Temperature distribution (272 sec)

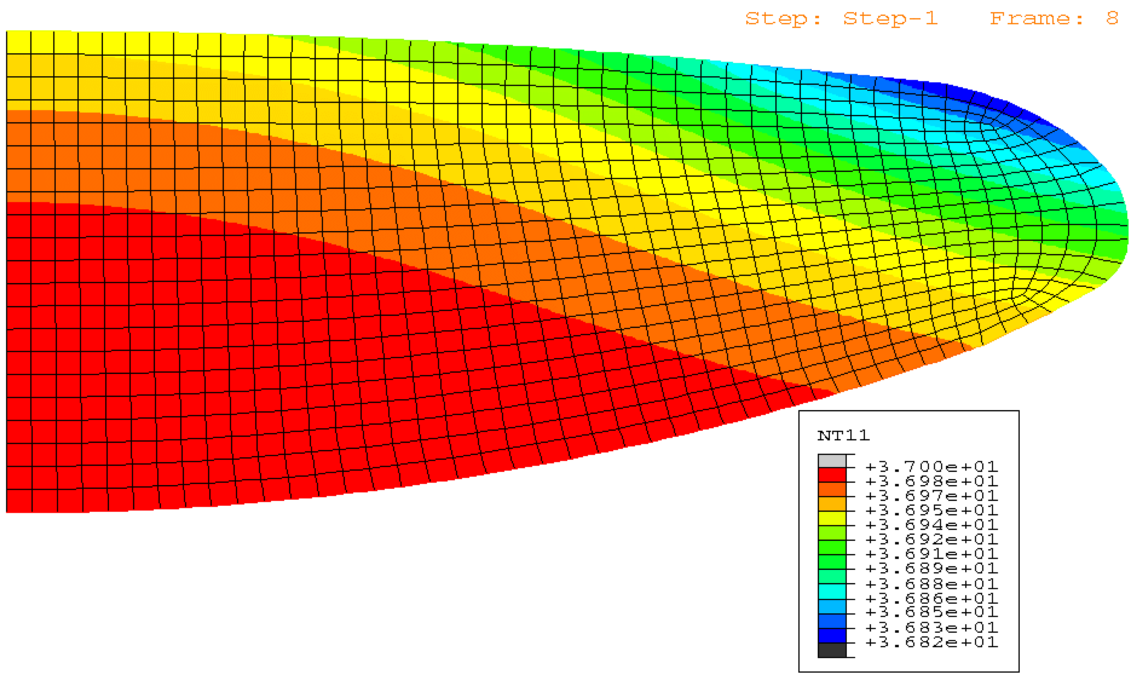

Fig.5.11 Lens Temperature distribution (8 sec)

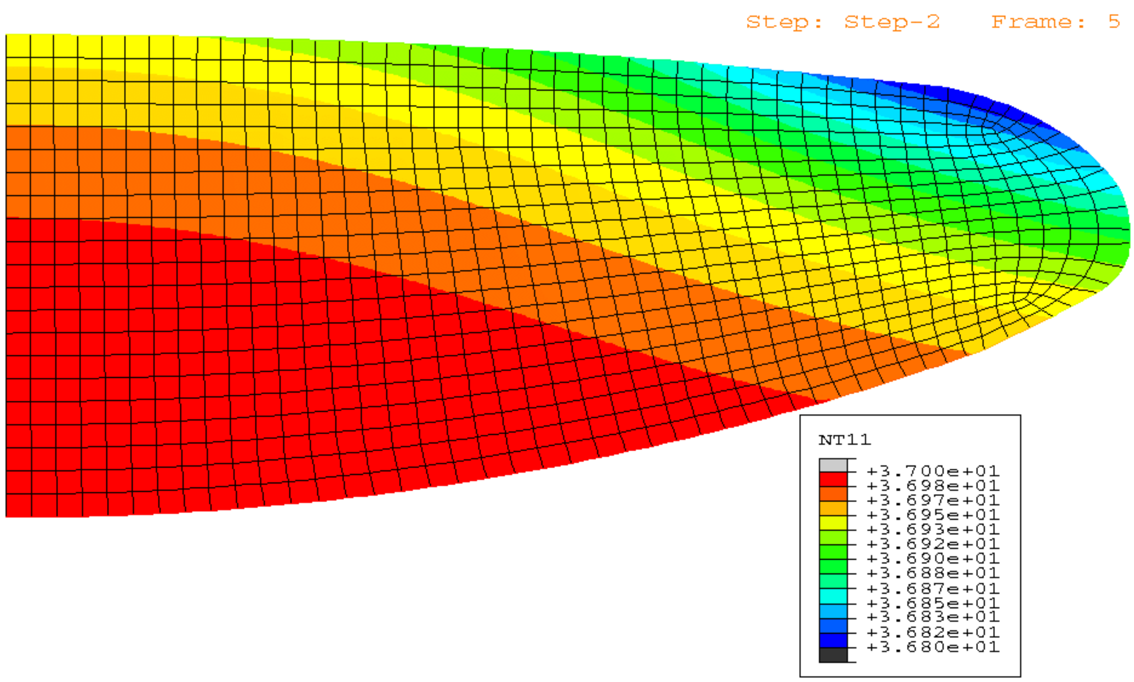

Fig.5.12 Lens Temperature distribution (8.5 sec)

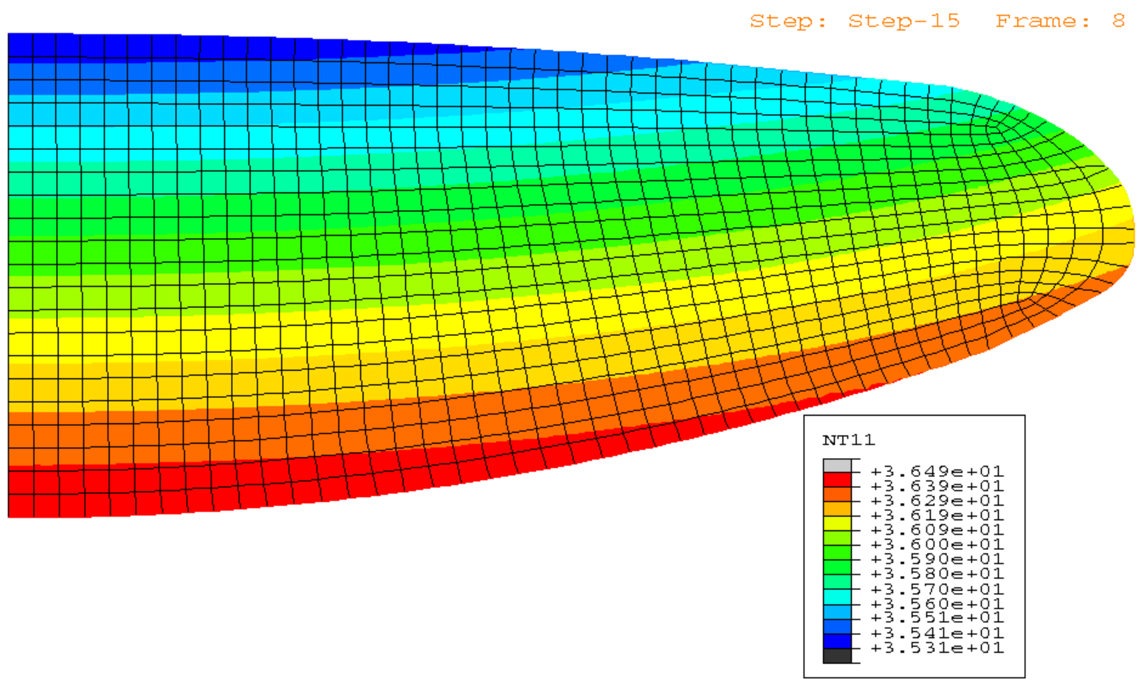

Fig.5.13 Lens Temperature distribution (67.5 sec)

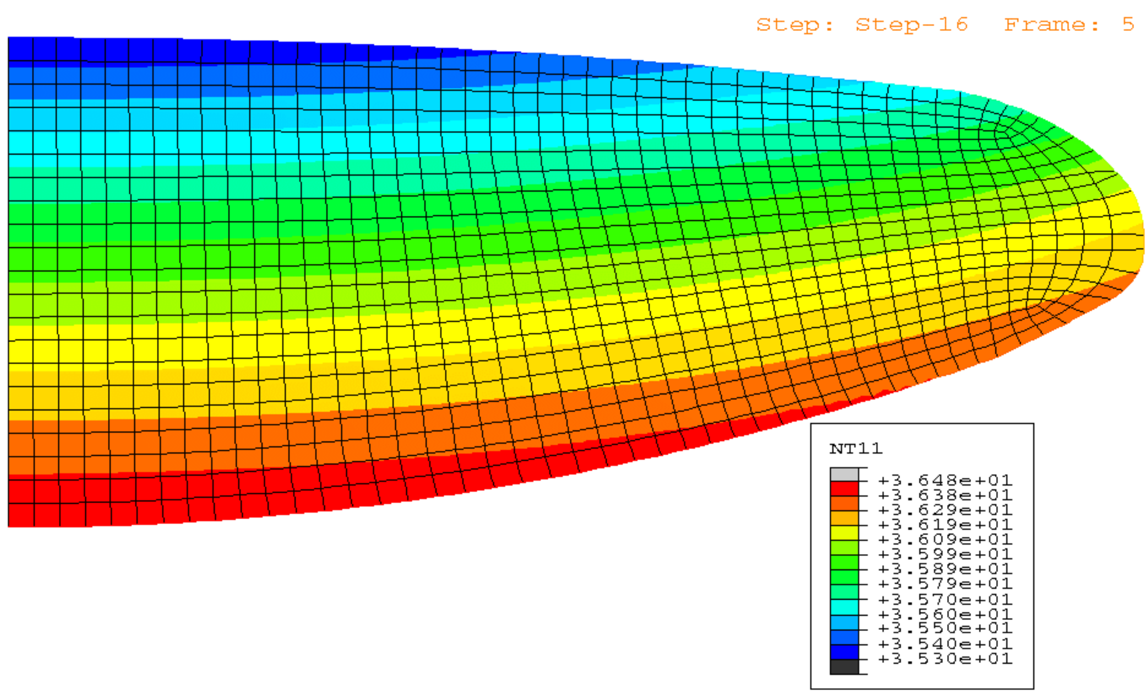

Fig.5.14 Lens Temperature distribution (68 sec)

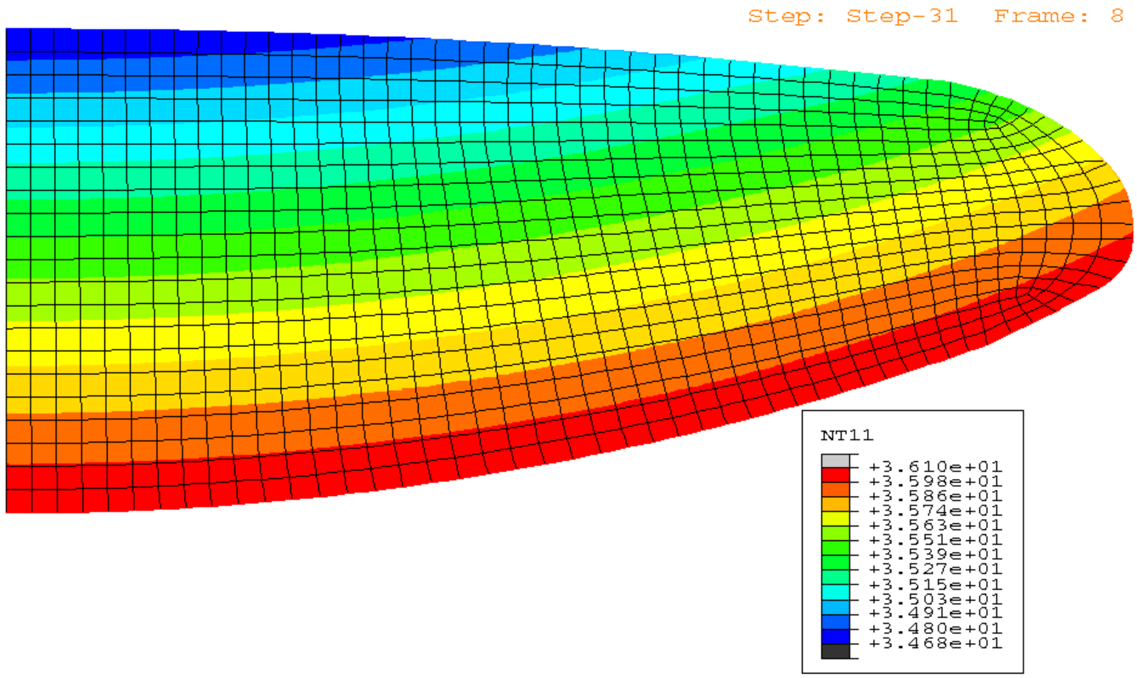

Fig.5.15 Lens Temperature distribution (135.5 sec)

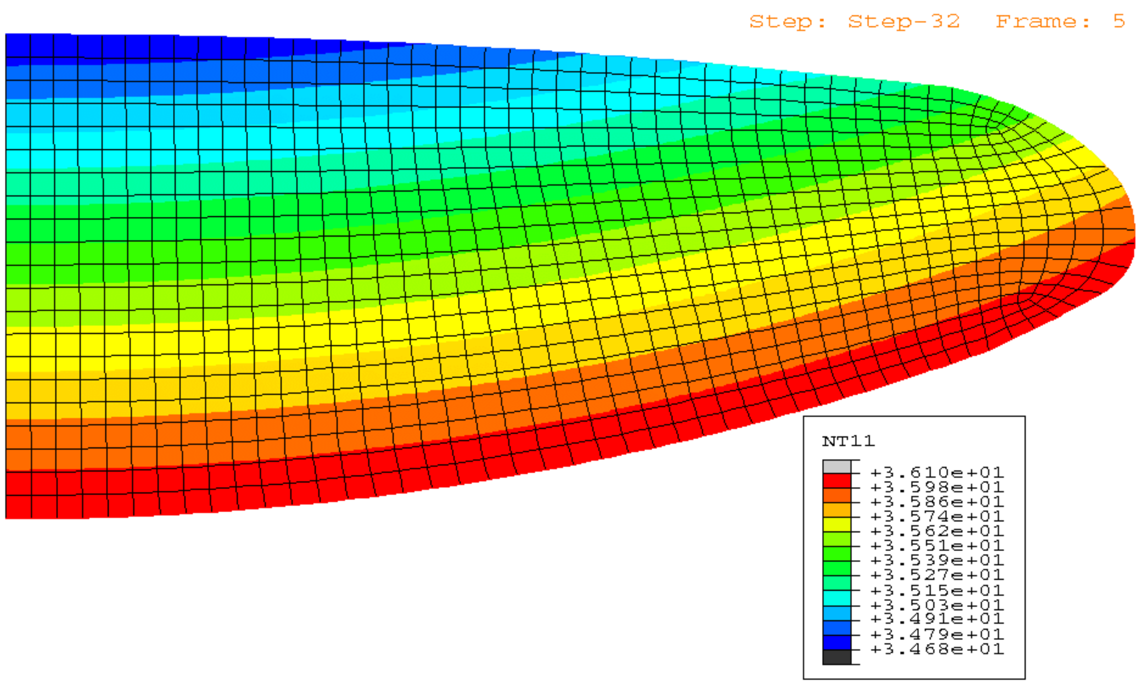

Fig.5.16 Lens Temperature distribution (136 sec)

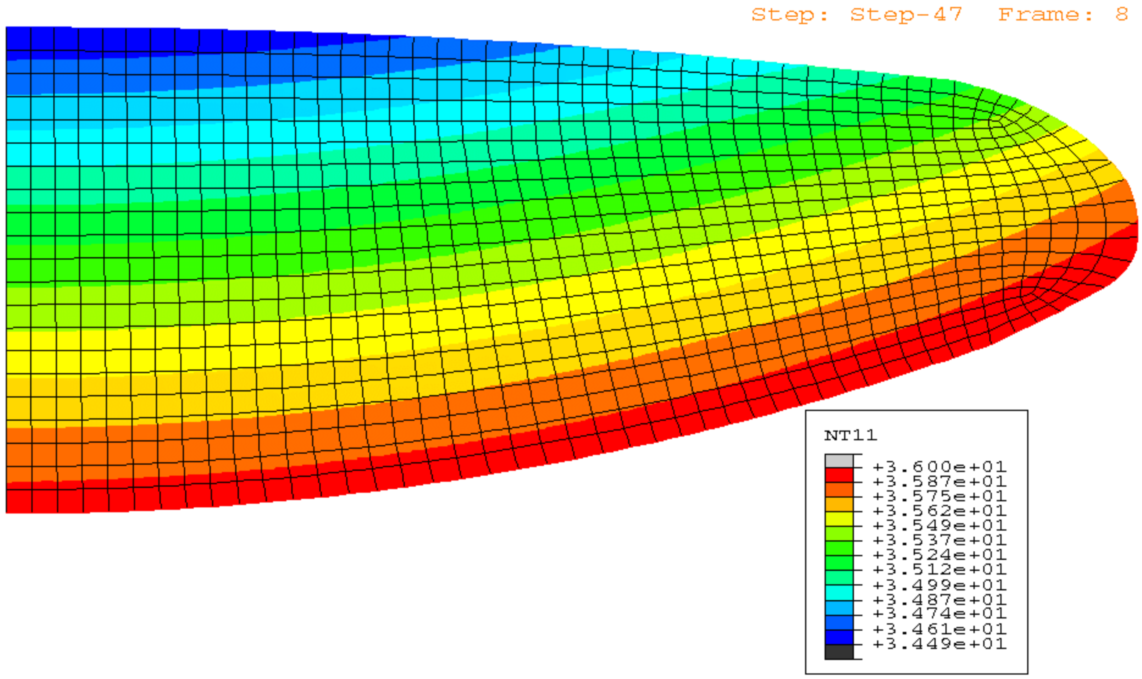

Fig.5.17 Lens Temperature distribution (203.5 sec)

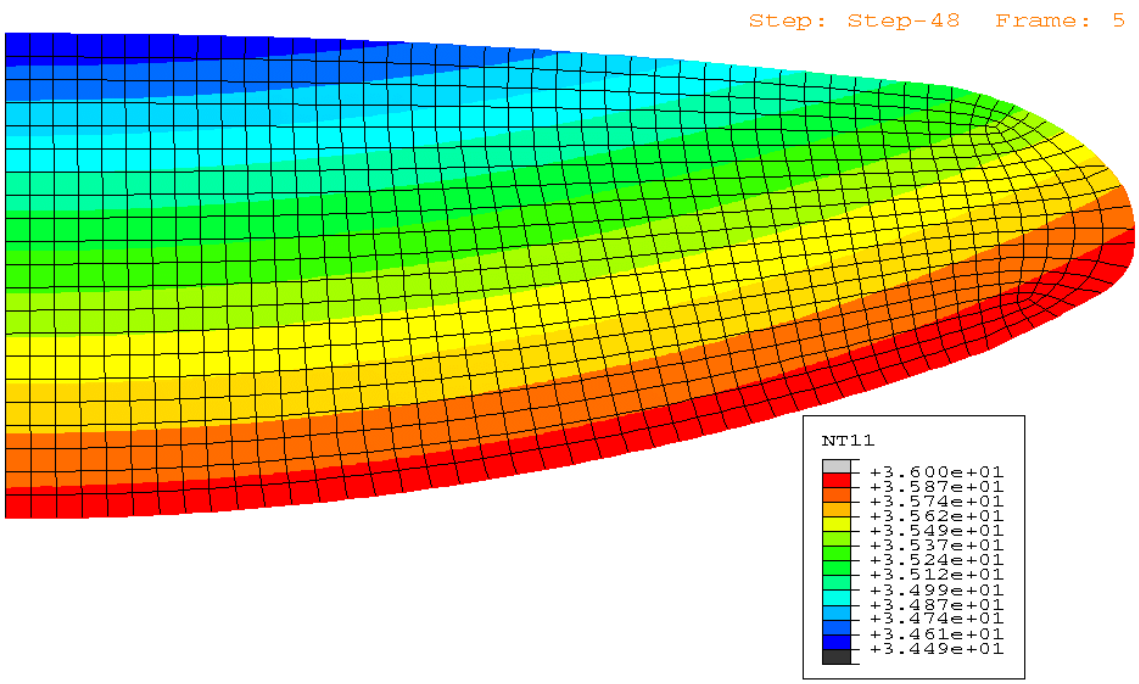

Fig.5.18 Lens Temperature distribution (204 sec)

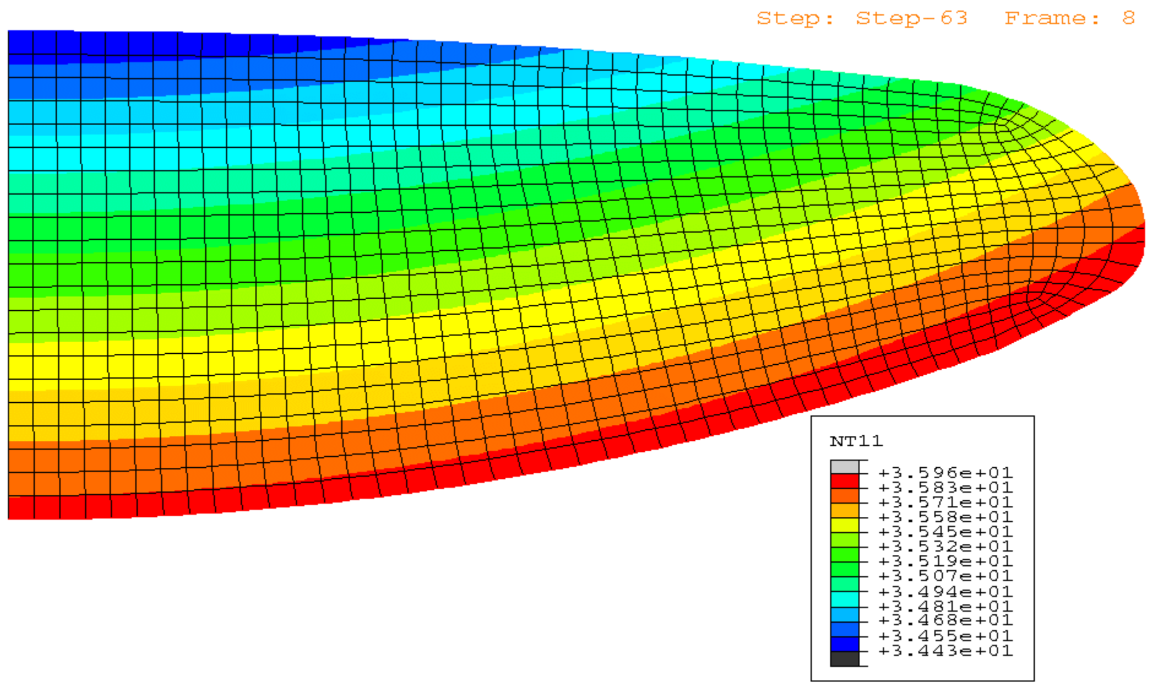

Fig.5.19 Lens Temperature distribution (271.5 sec)

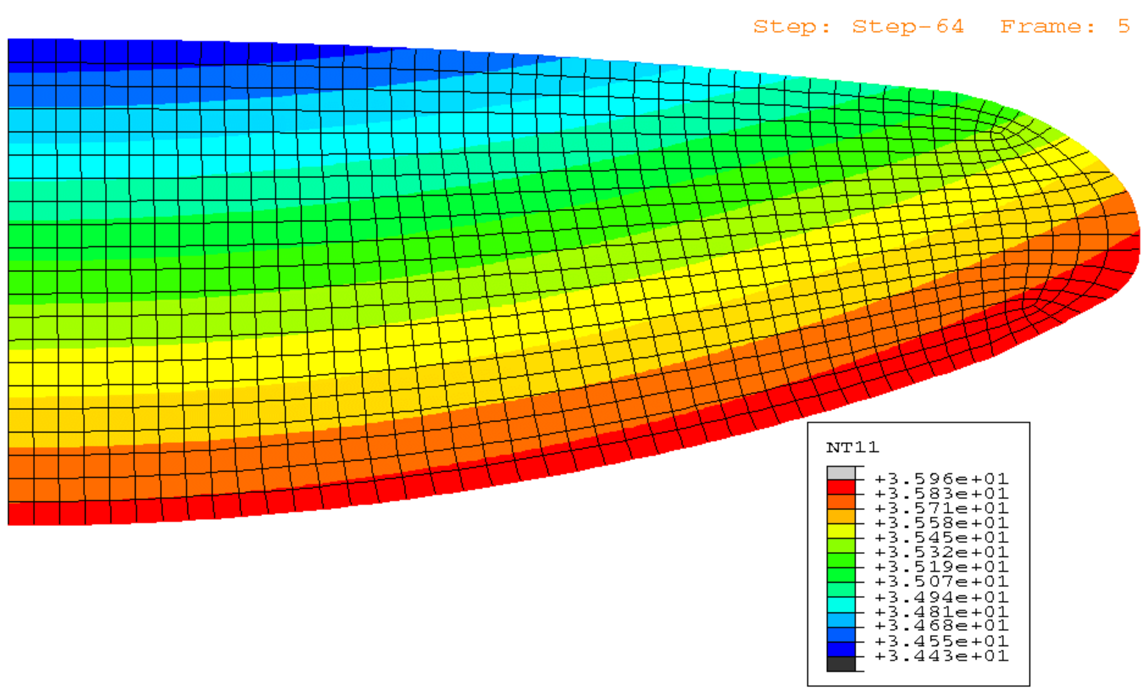

Fig.5.20 Lens Temperature distribution (272 sec)

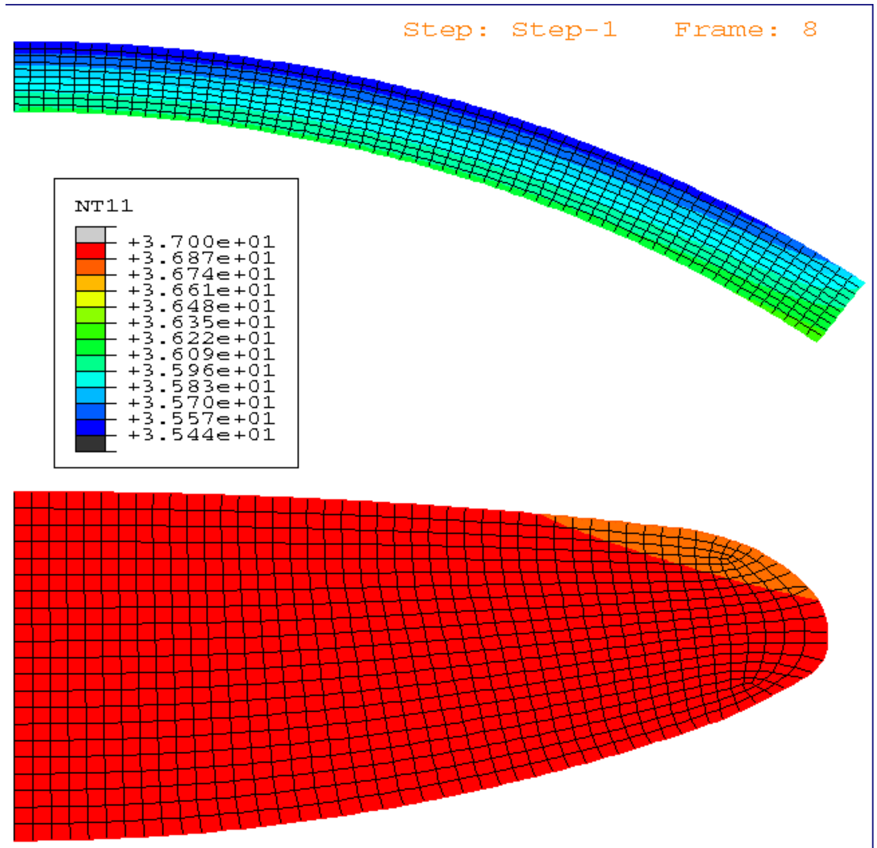

Fig.5.21 Cornea-Lens Temperature distribution (8 sec)

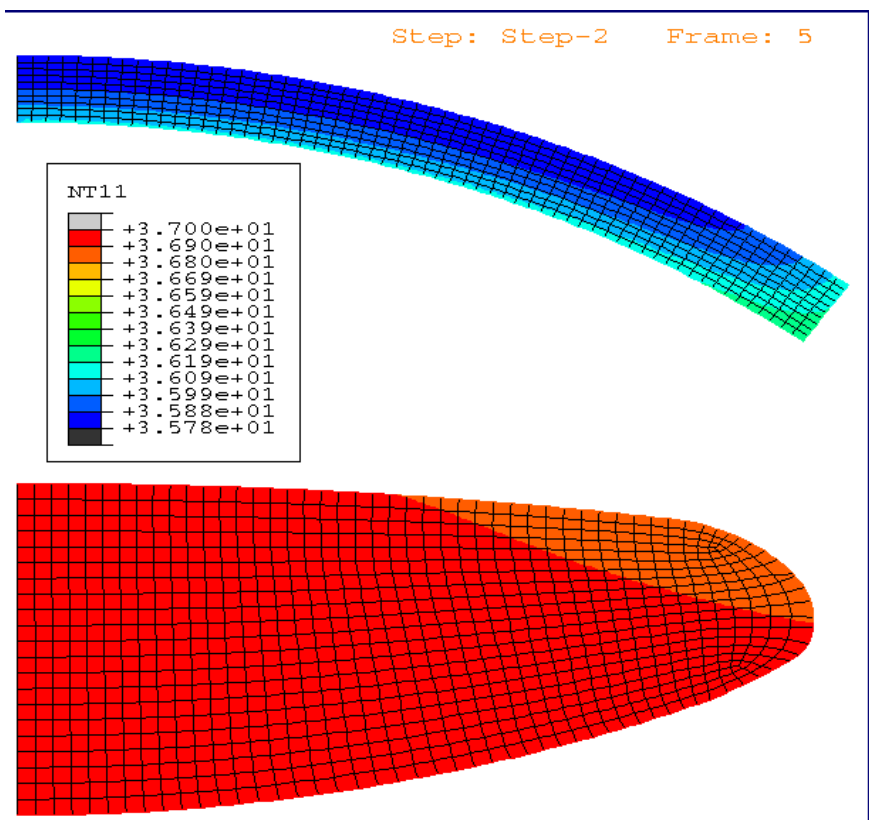

Fig.5.22 Cornea-Lens Temperature distribution (8.5 sec)

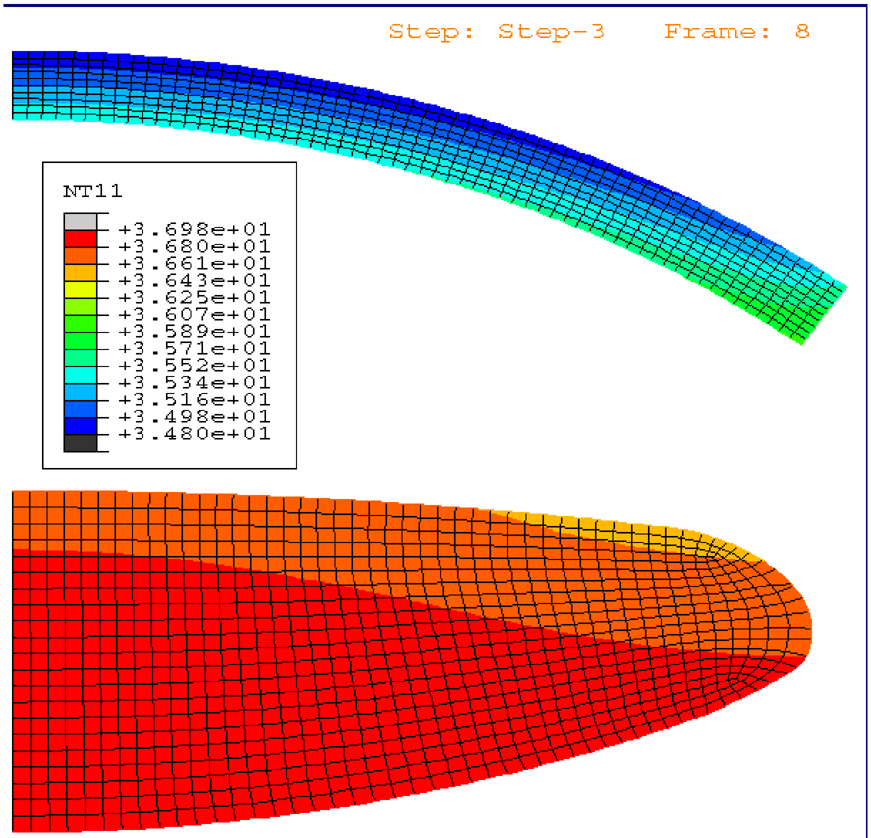

Fig.5.23 Cornea-Lens Temperature distribution (16.5 sec)

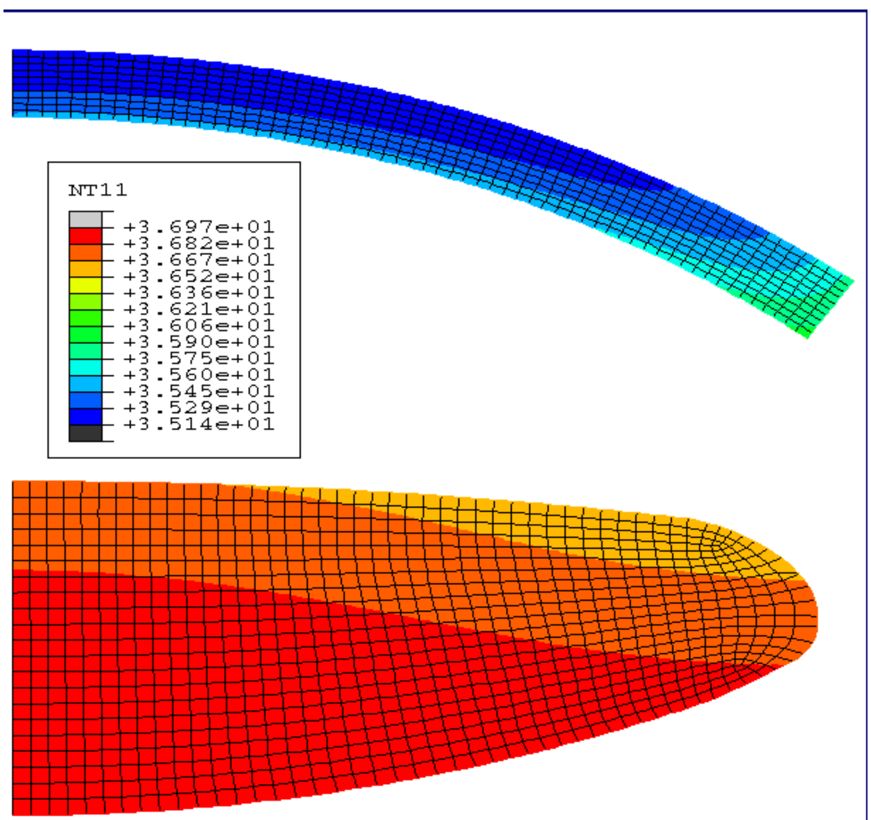

Fig.5.24 Cornea-Lens Temperature distribution (17 sec)

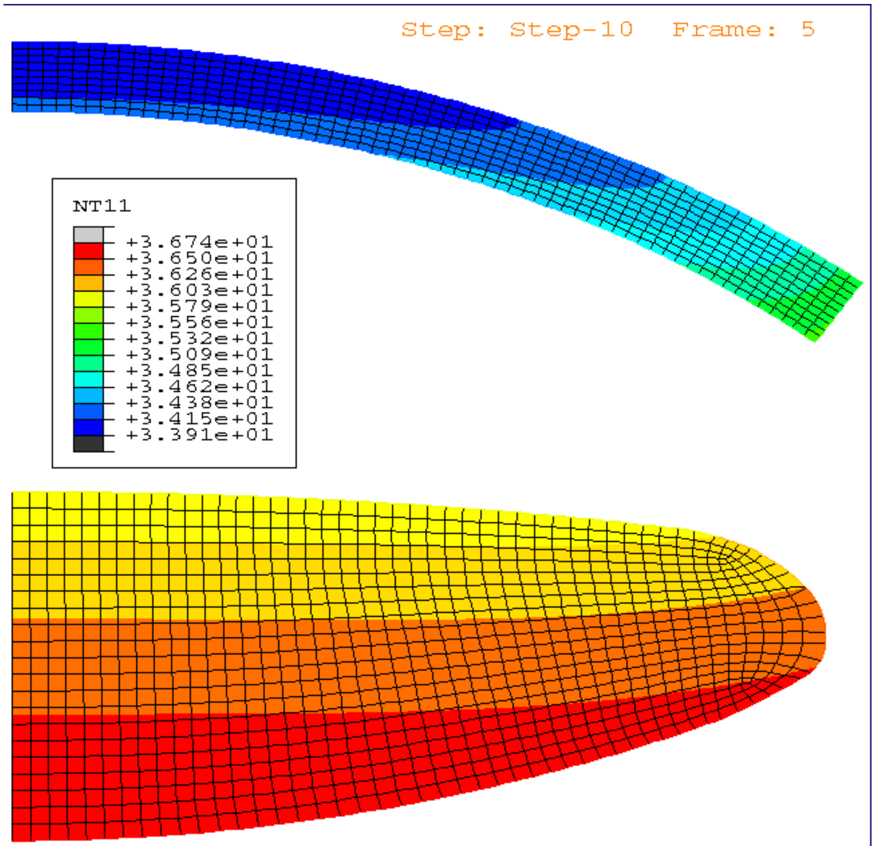

Fig.5.25 Cornea-Lens Temperature distribution (42.5 sec)

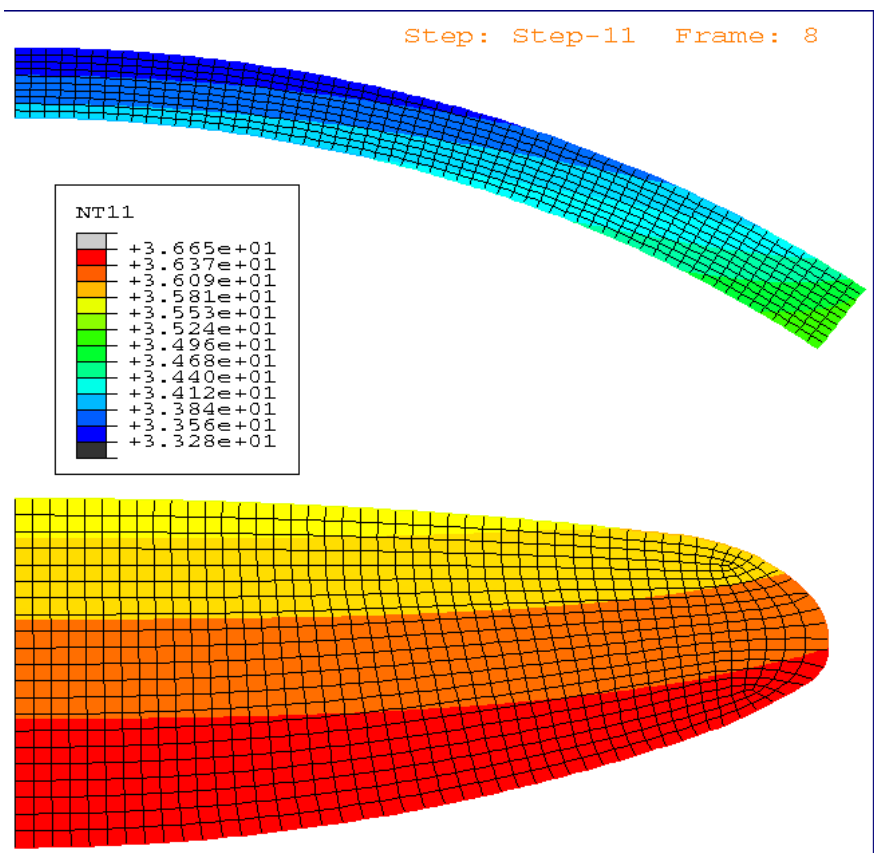

Fig.5.26 Cornea-Lens Temperature distribution (50.5 sec)

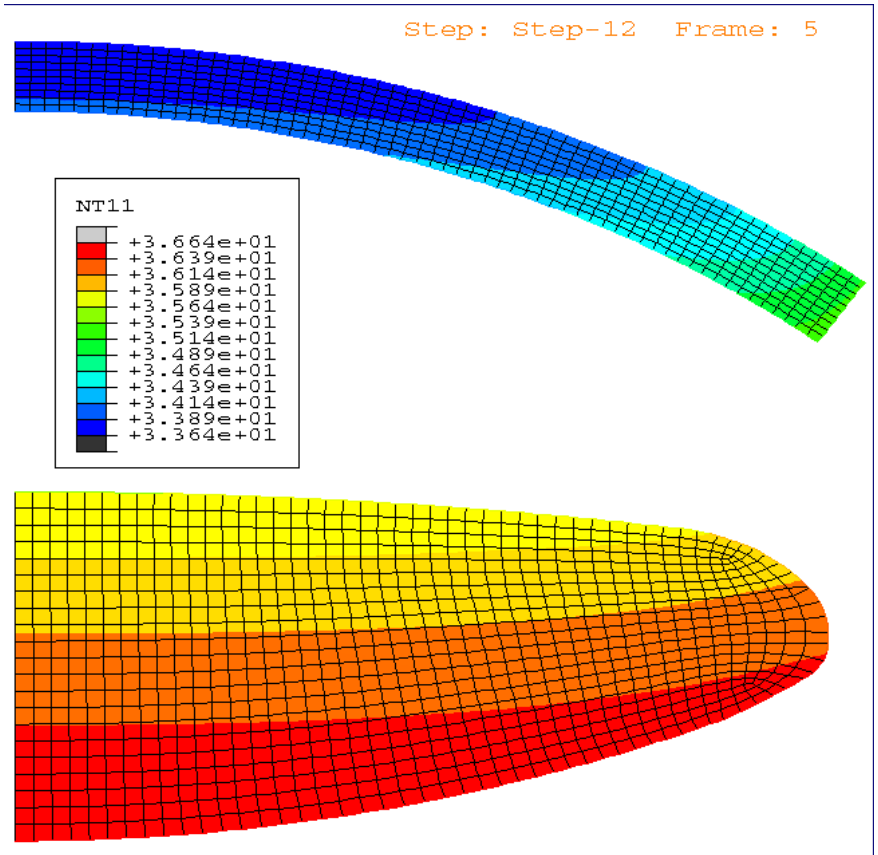

Fig.5.27 Cornea-Lens Temperature distribution (51 sec)

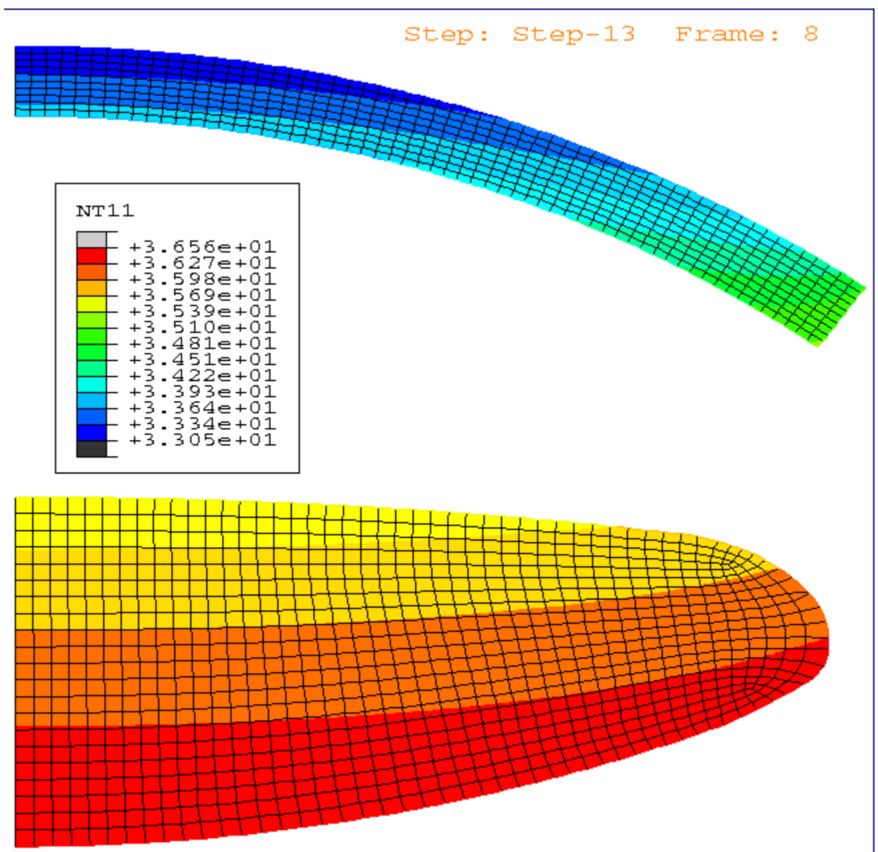

Fig.5.28 Cornea-Lens Temperature distribution (59 sec)

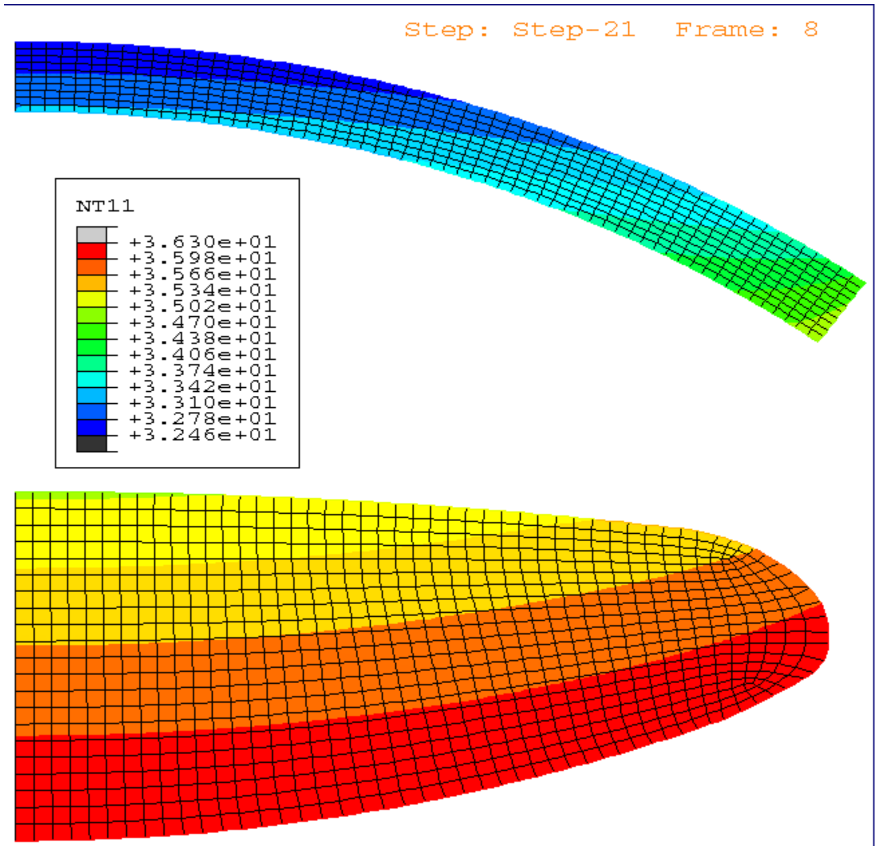

Fig.5.29 Cornea-Lens Temperature distribution (93 sec)

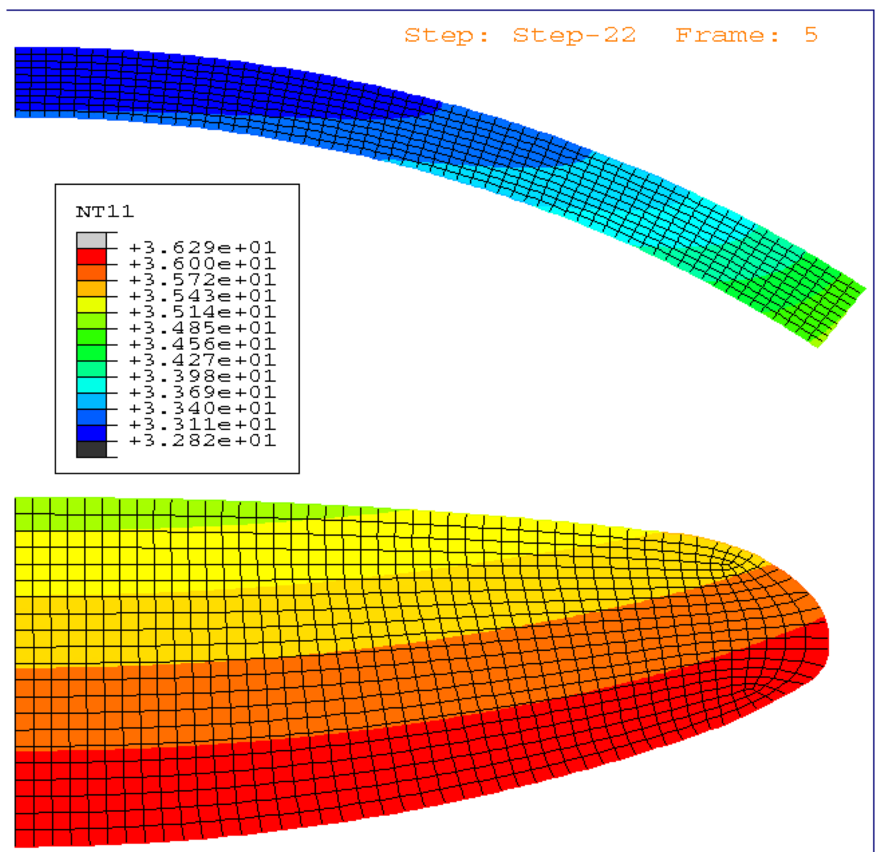

Fig.5.30 Cornea-Lens Temperature distribution (93.5 sec)

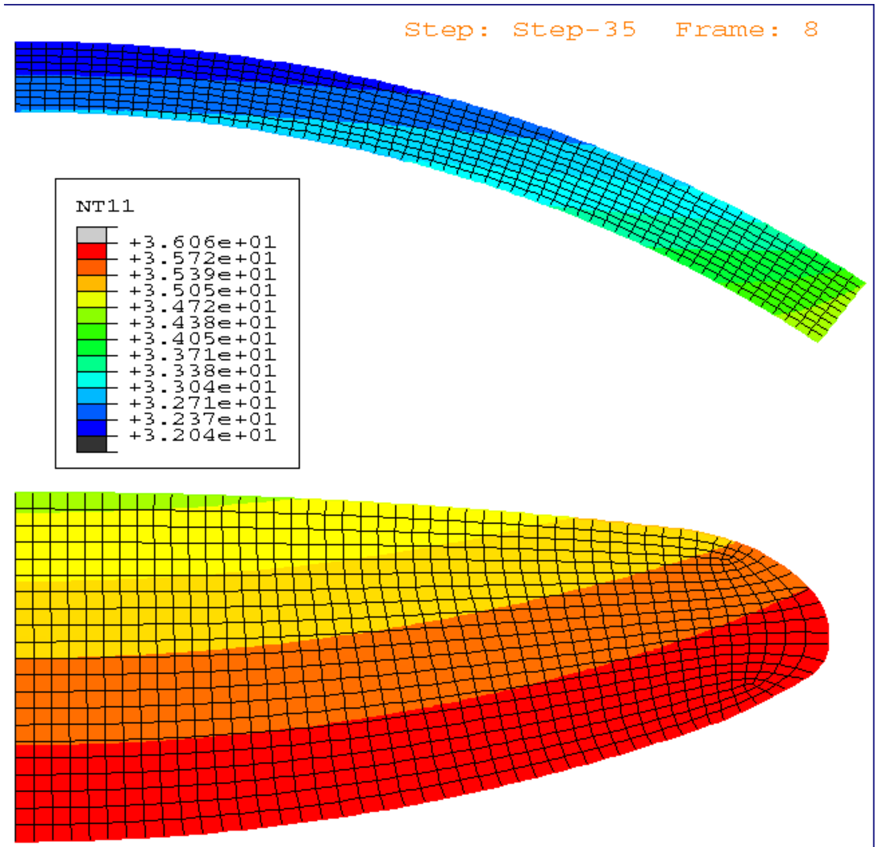

Fig.5.31 Cornea-Lens Temperature distribution (152.5 sec)

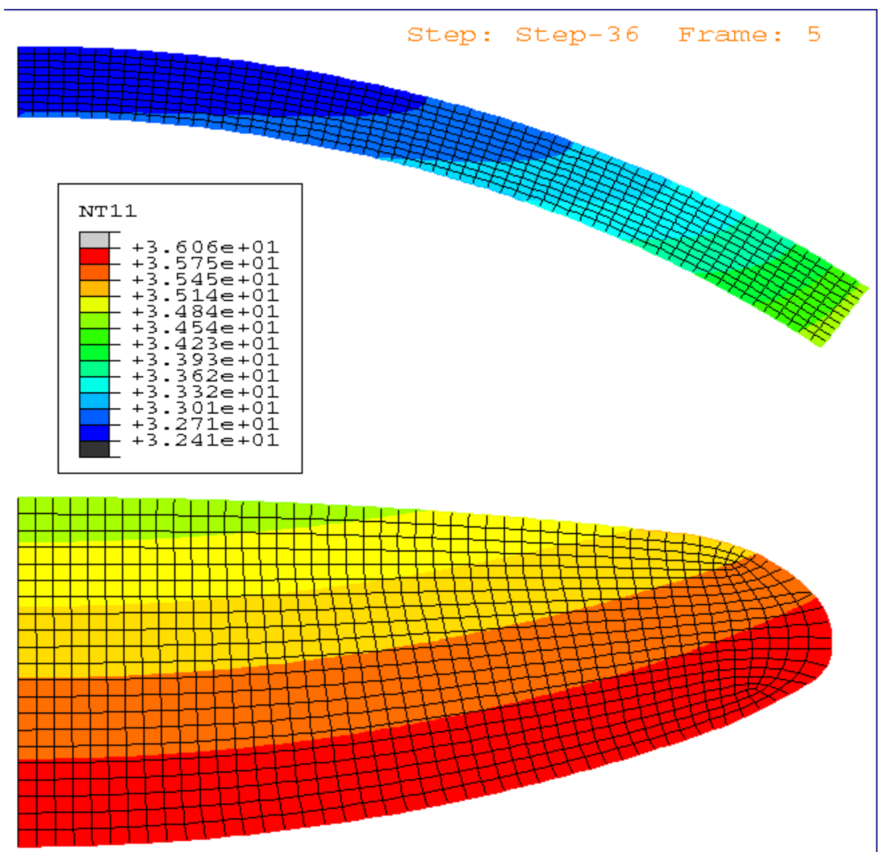

Fig.5.32 Cornea-Lens Temperature distribution (153 sec)

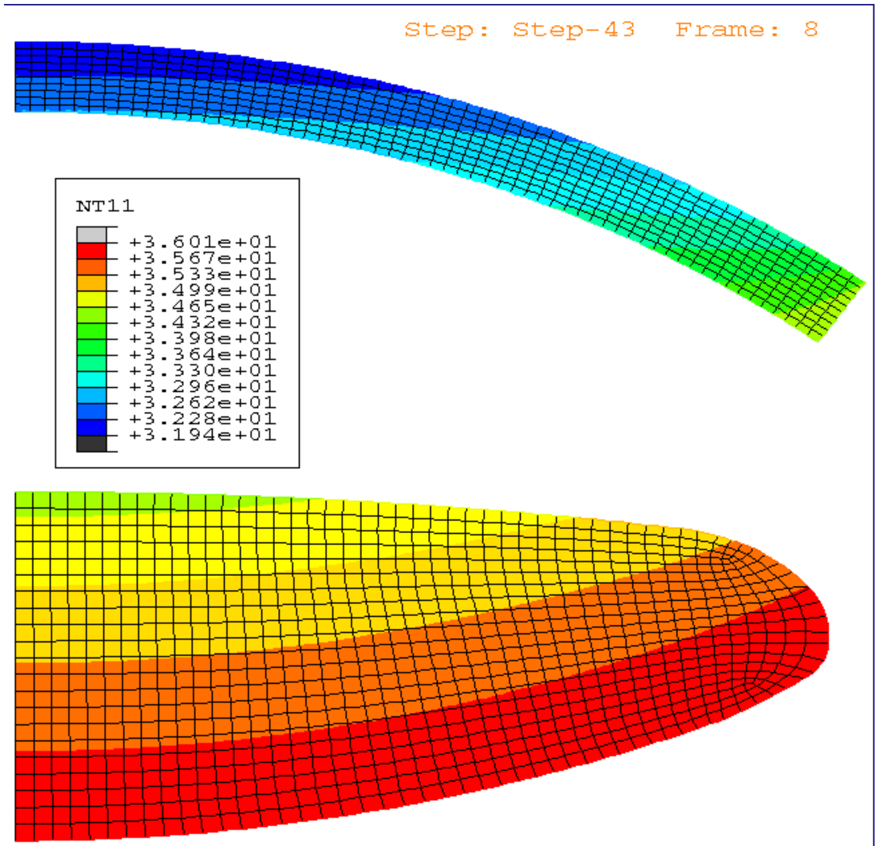

Fig.5.33 Cornea-Lens Temperature distribution (186.5 sec)

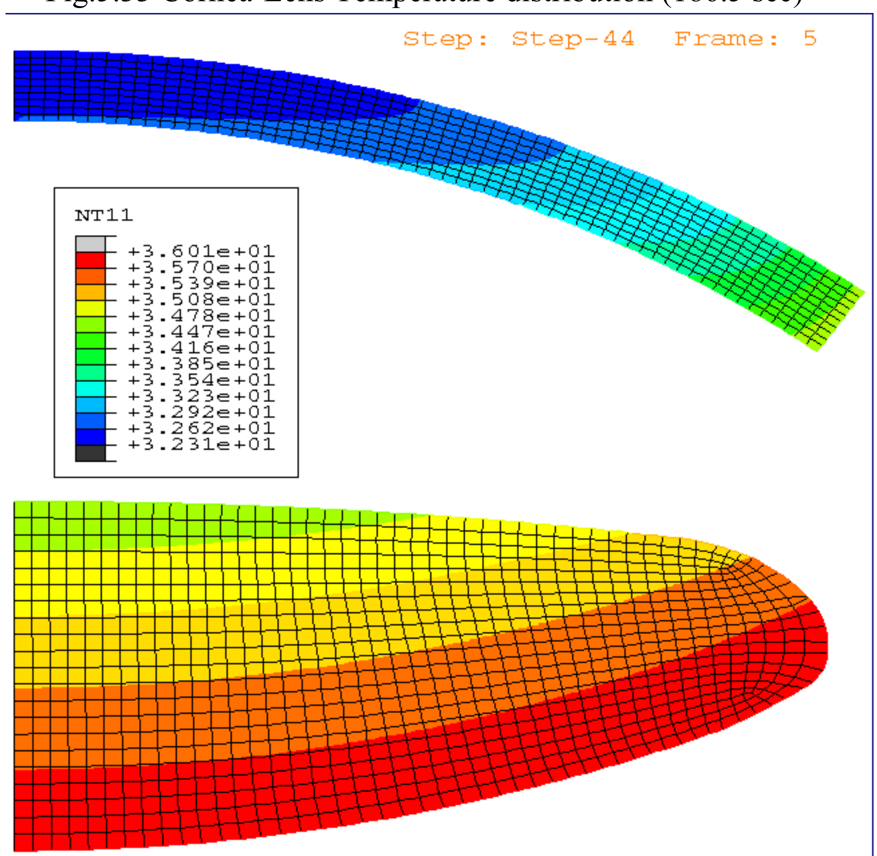

Fig.5.34 Cornea-Lens Temperature distribution (187 sec)

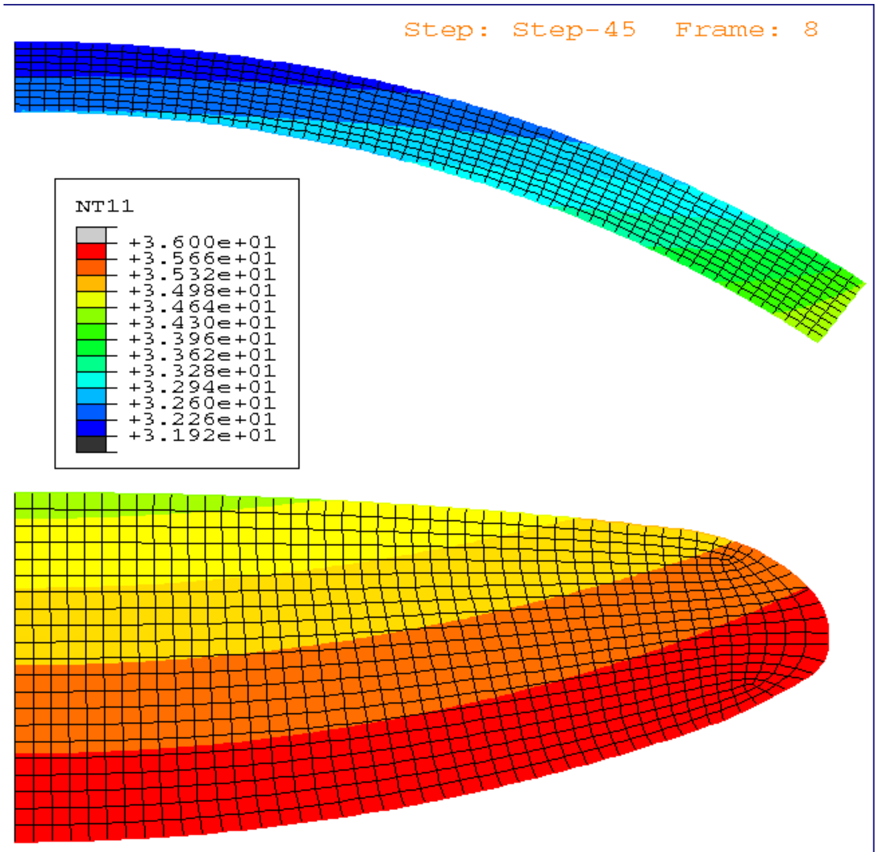

Fig.5.35 Cornea-Lens Temperature distribution (187.5 sec)

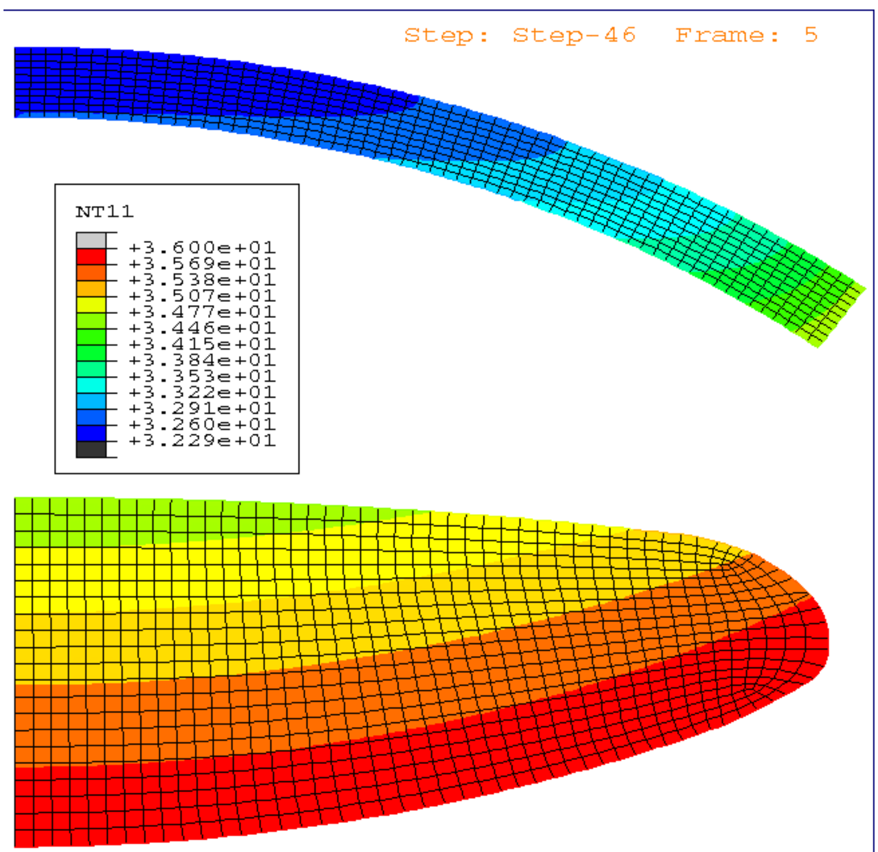

Fig.5.36 Cornea-Lens Temperature distribution (195.5 sec)

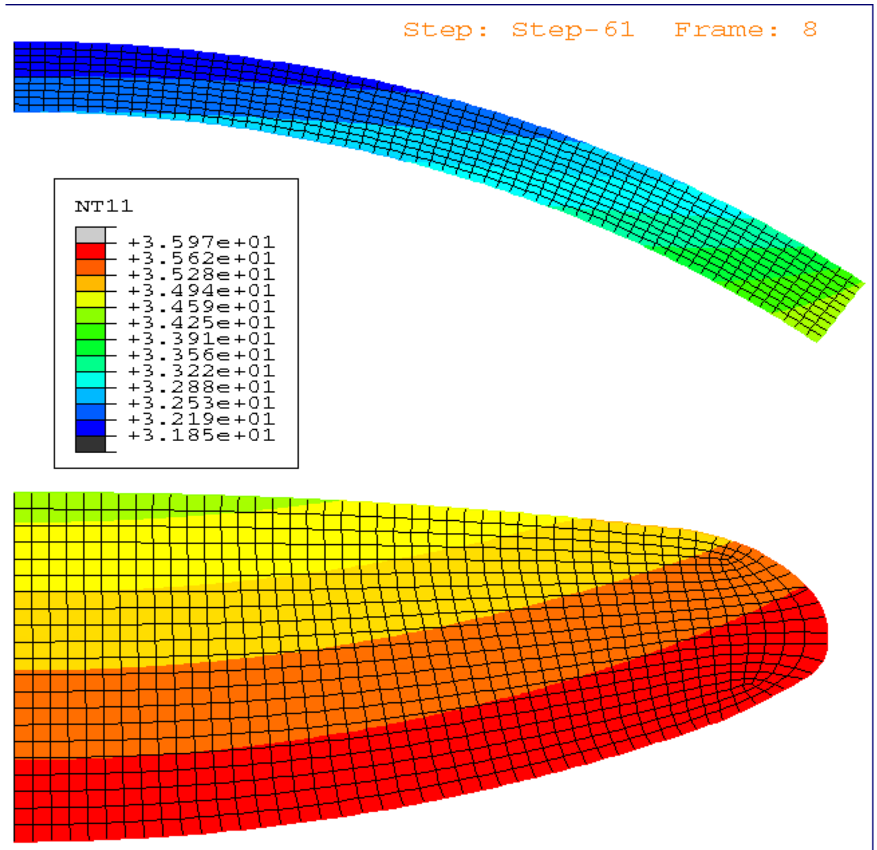

Fig.5.37 Cornea-Lens Temperature distribution (263 sec)

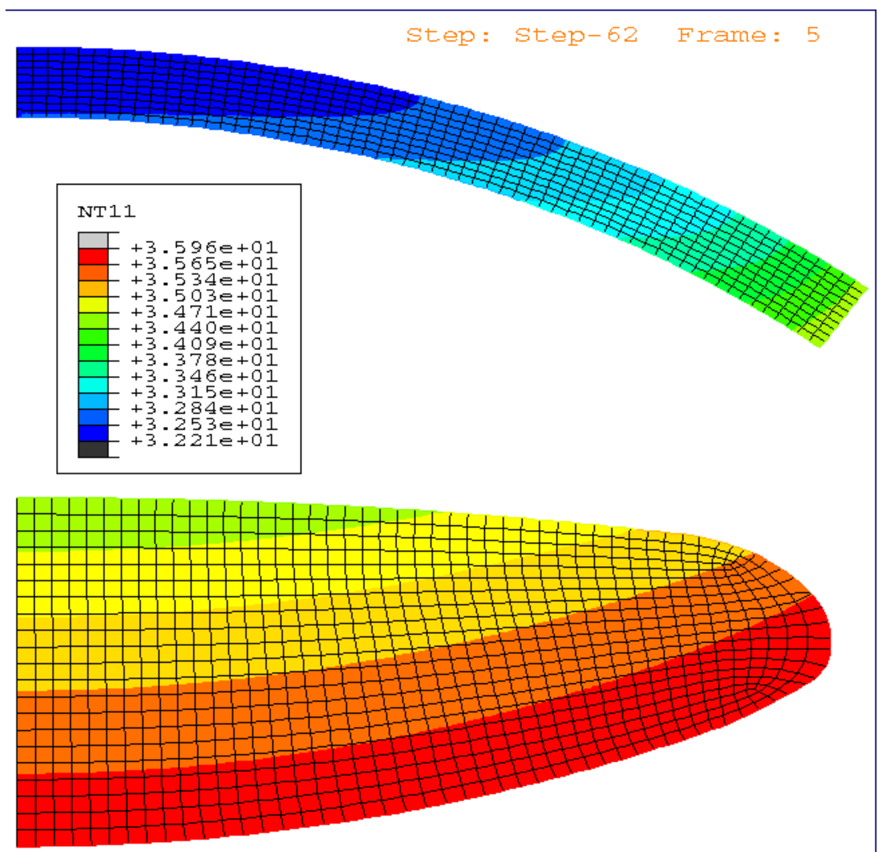

Fig.5.38 Cornea-Lens Temperature distribution (263.5 sec)

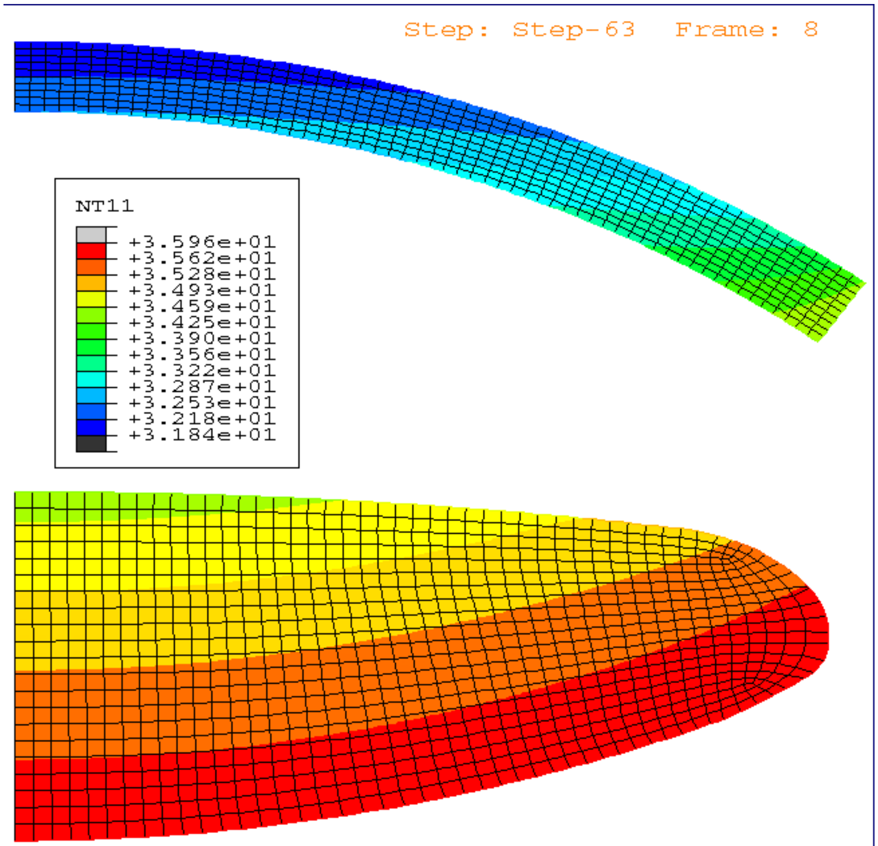

Fig.5.39 Cornea-Lens Temperature distribution (271.5 sec)

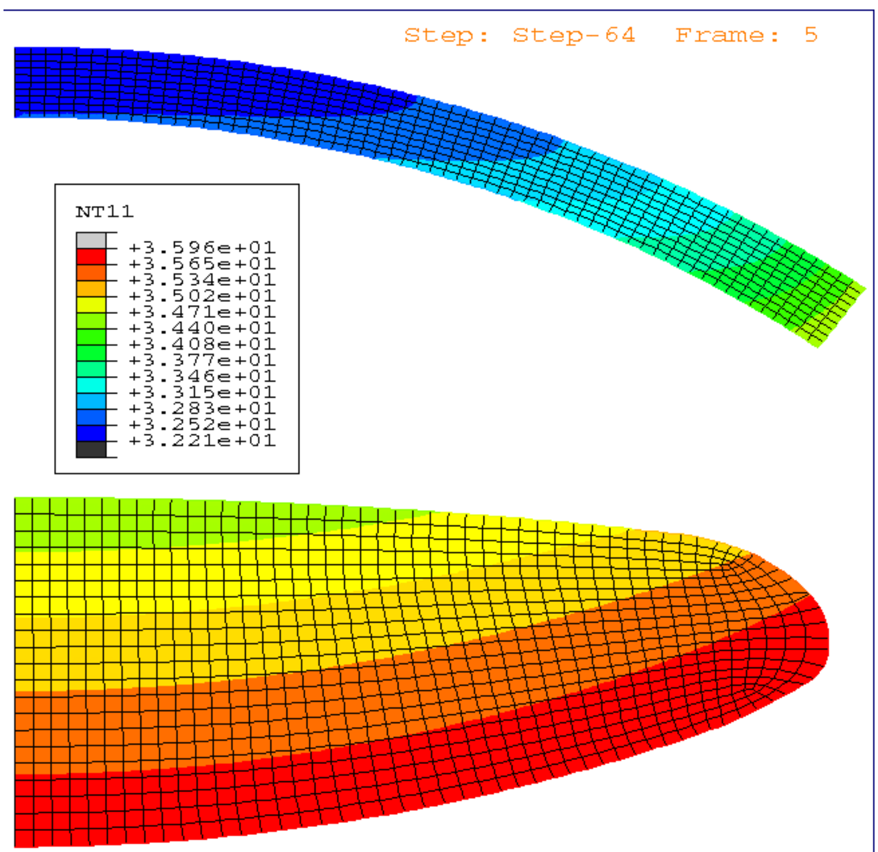

Fig.5.40 Cornea-Lens Temperature distribution (272 sec)

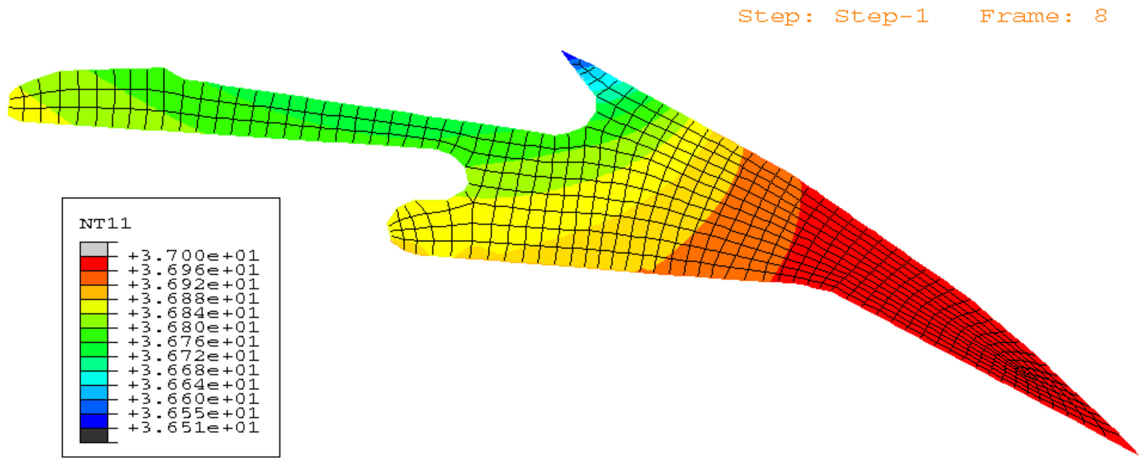

Fig.5.41 Iris Temperature distribution (8 sec)

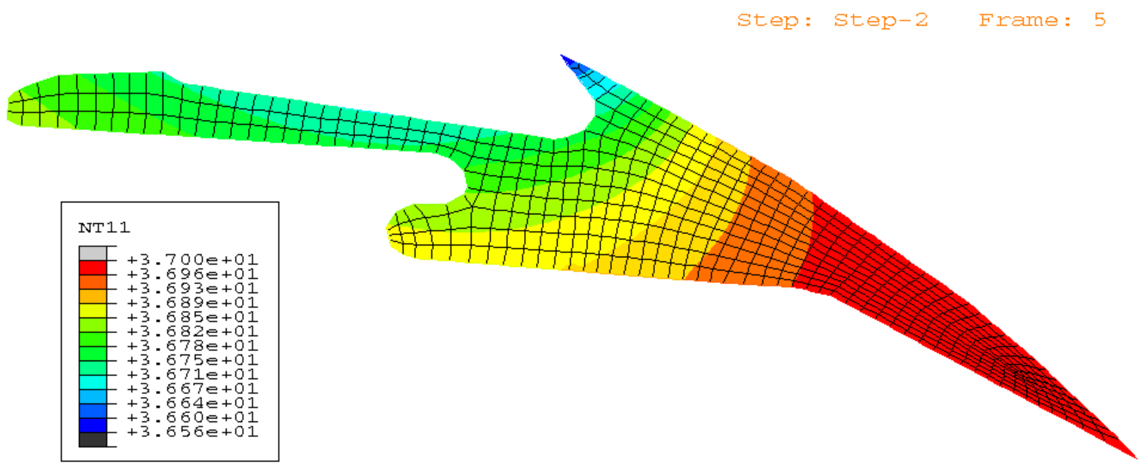

Fig.5.42 Iris Temperature distribution (8.5 sec)

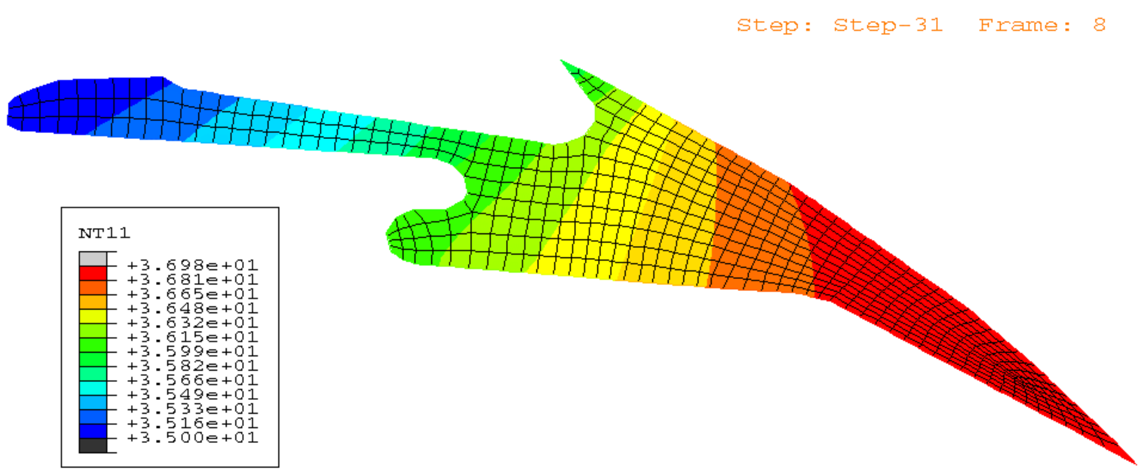

Fig.5.43 Iris Temperature distribution (135.5 sec)

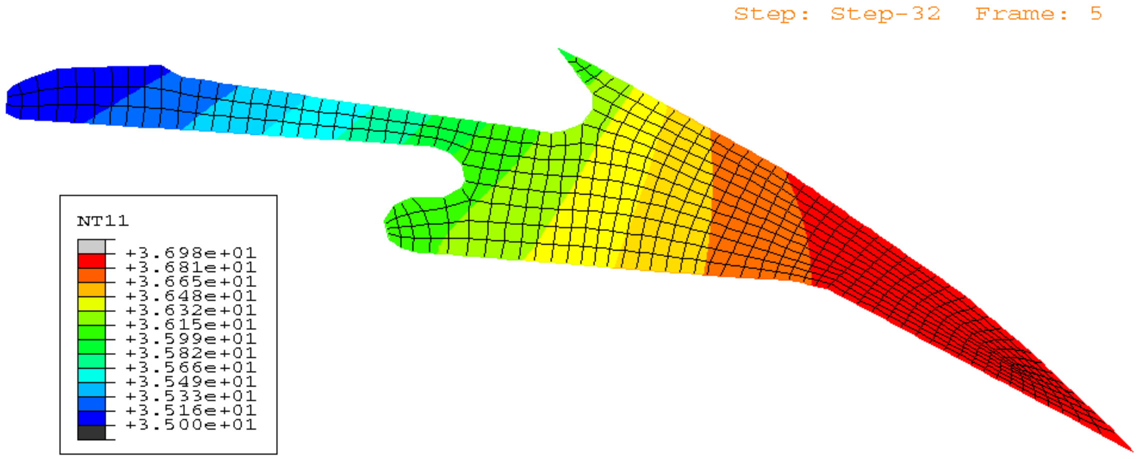

Fig.5.44 Iris Temperature distribution (136 sec)

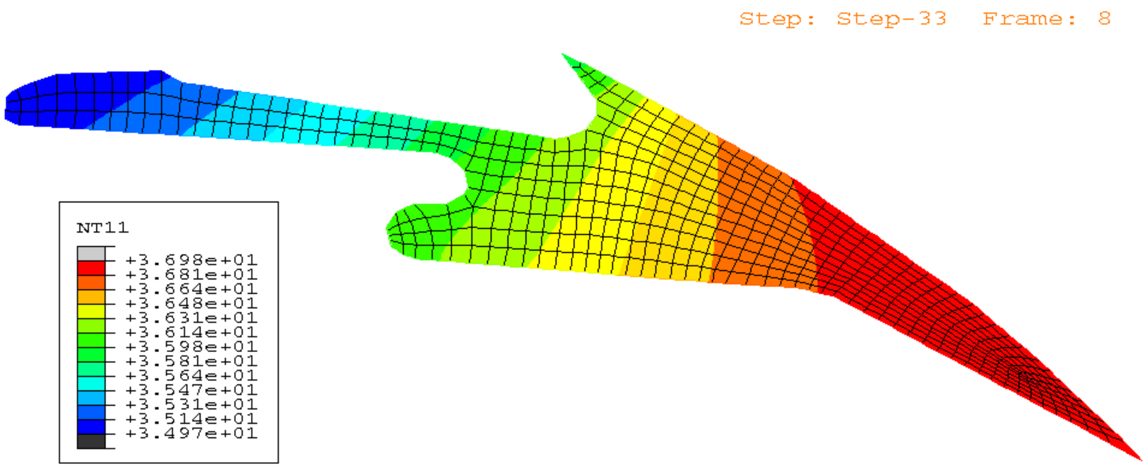

Fig.5.45 Iris Temperature distribution (144 sec)

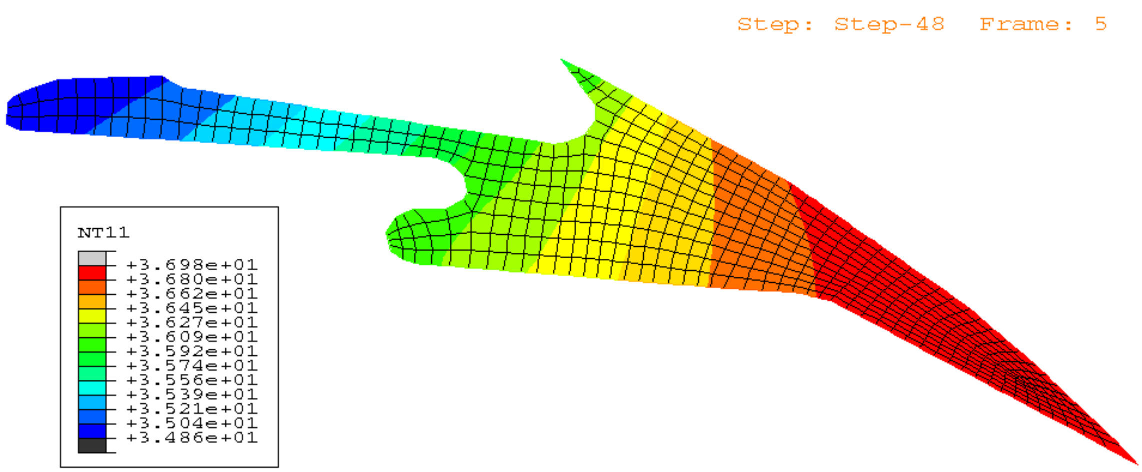

Fig.5.46 Iris Temperature distribution (204 sec)

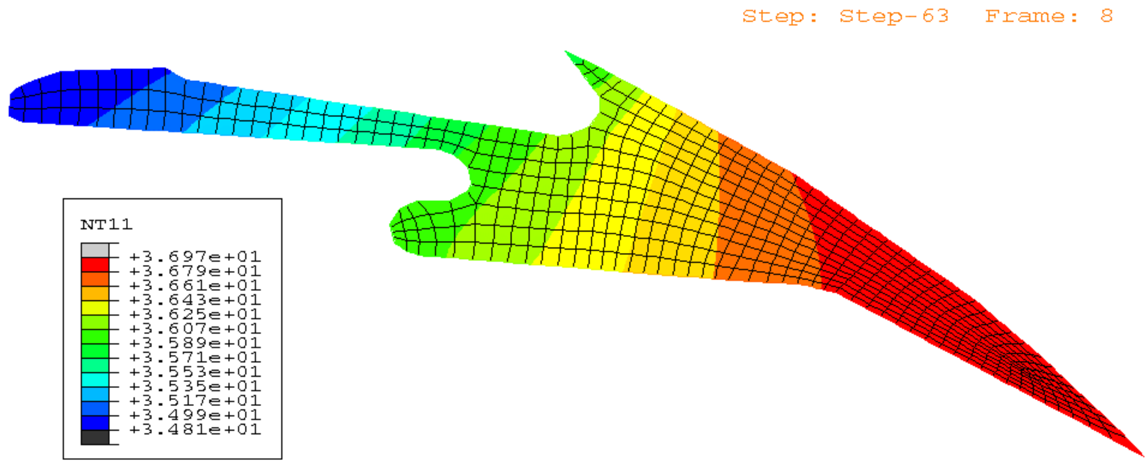

Fig.5.47 Iris Temperature distribution (271.5 sec)

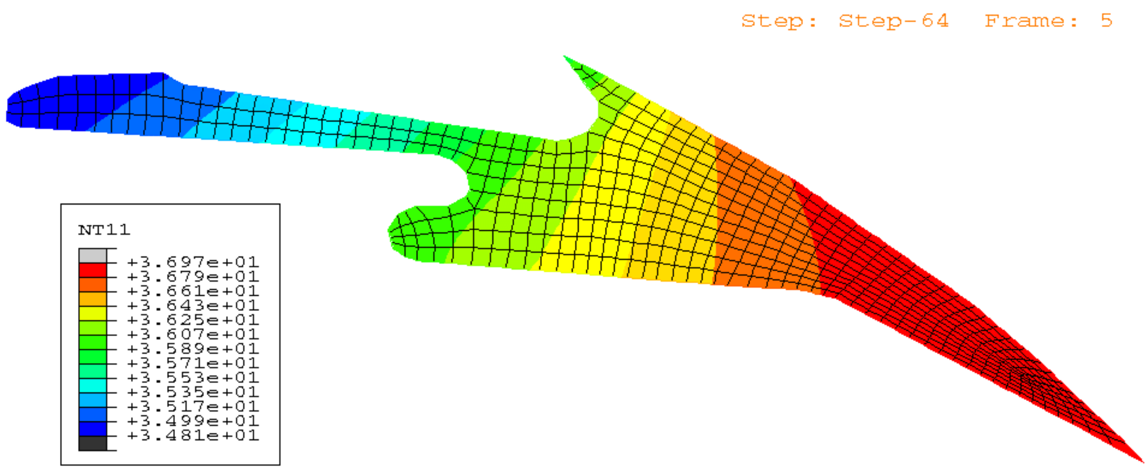

Fig.5.48 Iris Temperature distribution (272 sec)

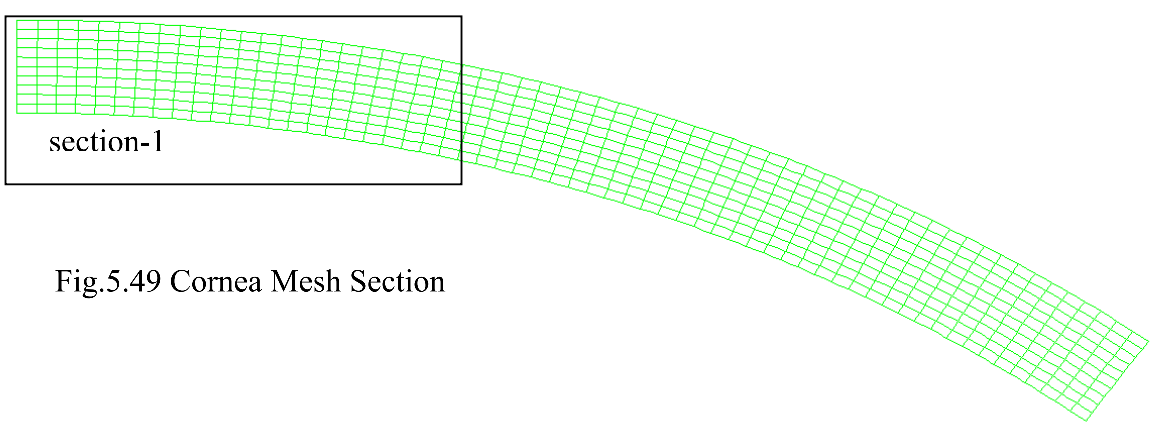

Fig.5.49 Cornea Mesh Section

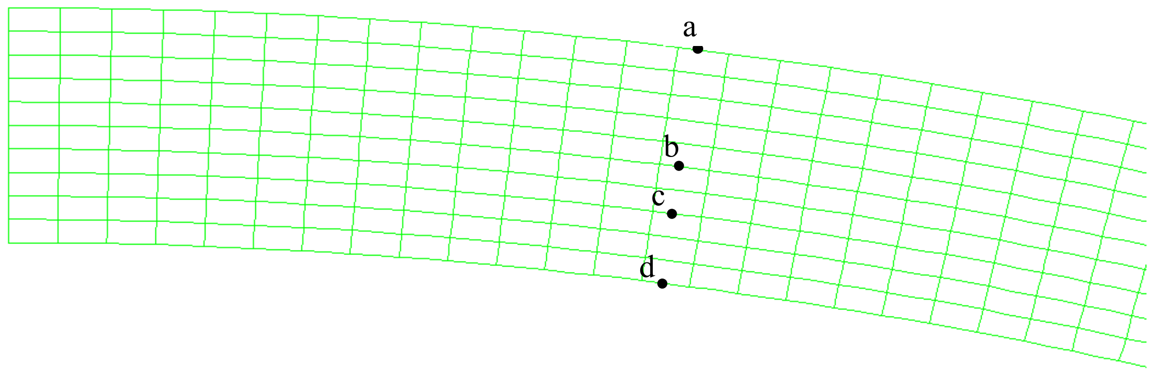

Fig.5.50 Cornea-section-1

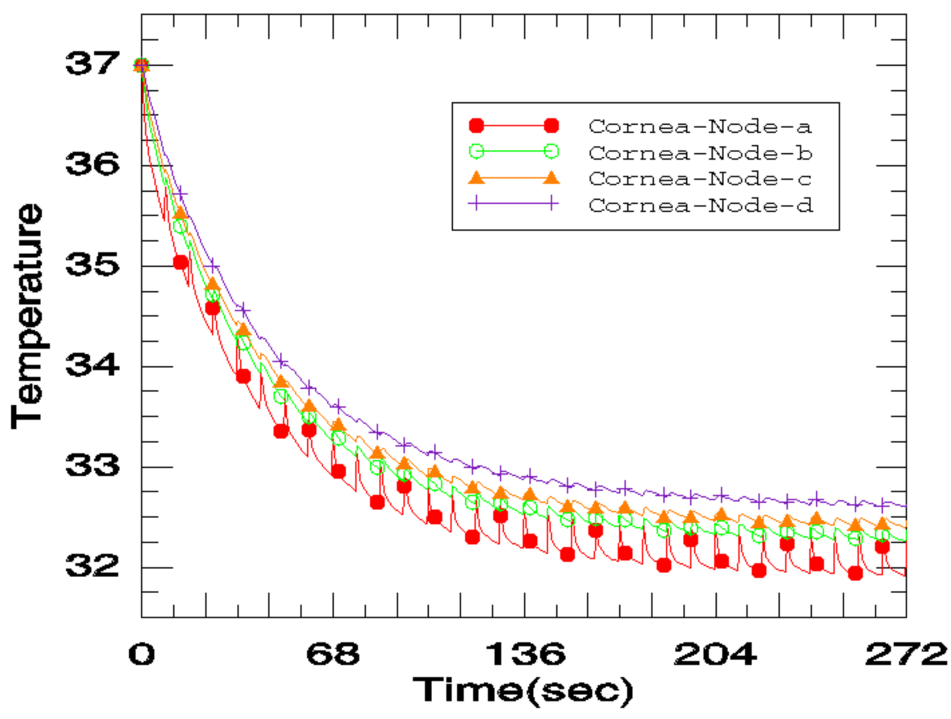

Fig.5.51 Temperature distribution through cornea at nodes (a, b, c, d)

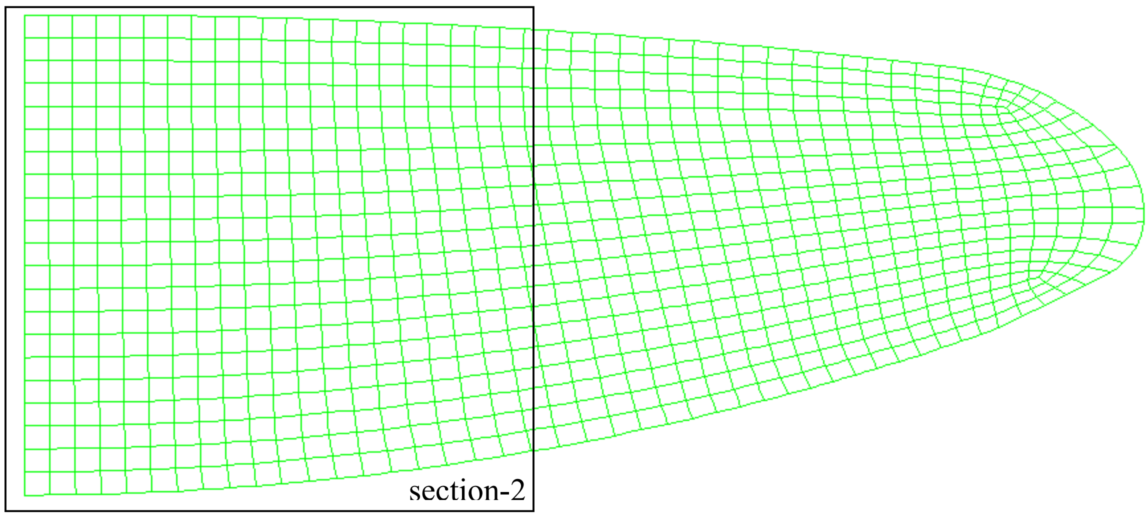

Fig.5.52 Lens Mesh Section

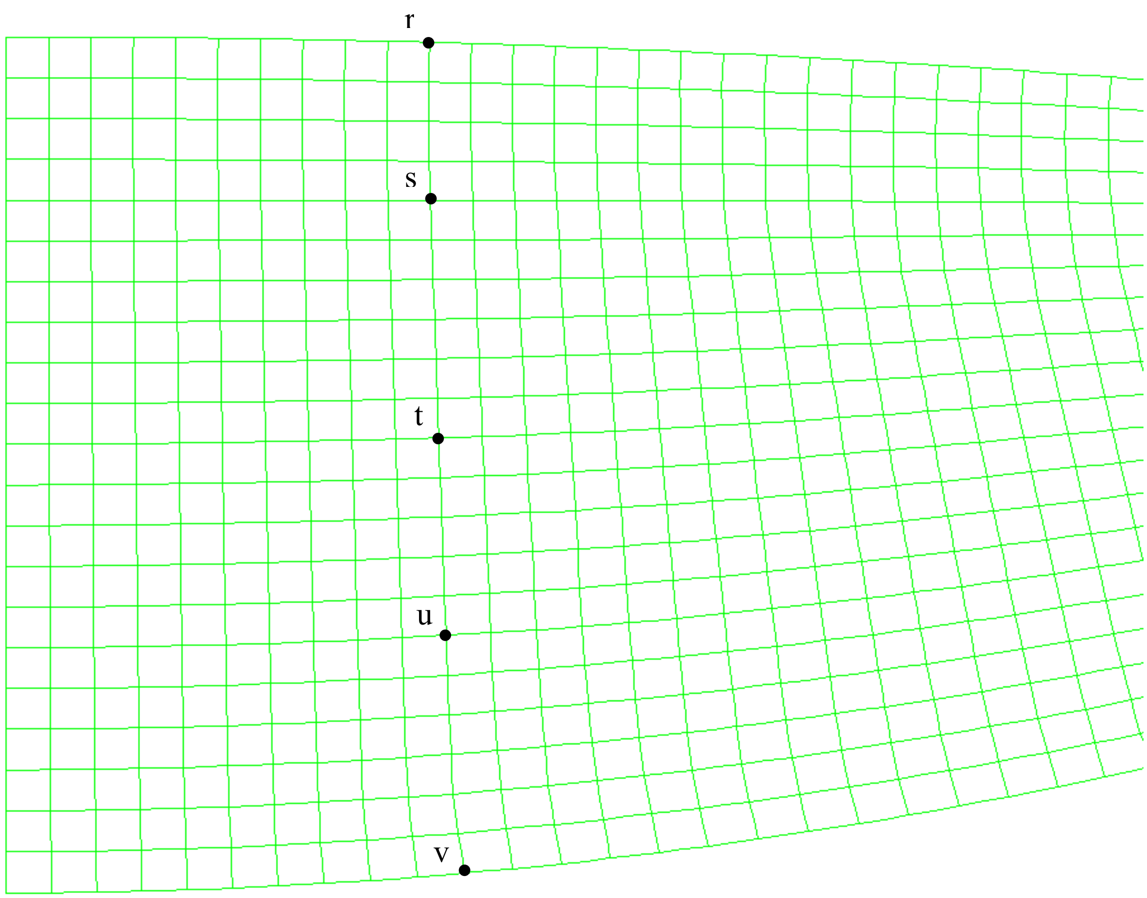

Fig.5.53 Lens Section-2

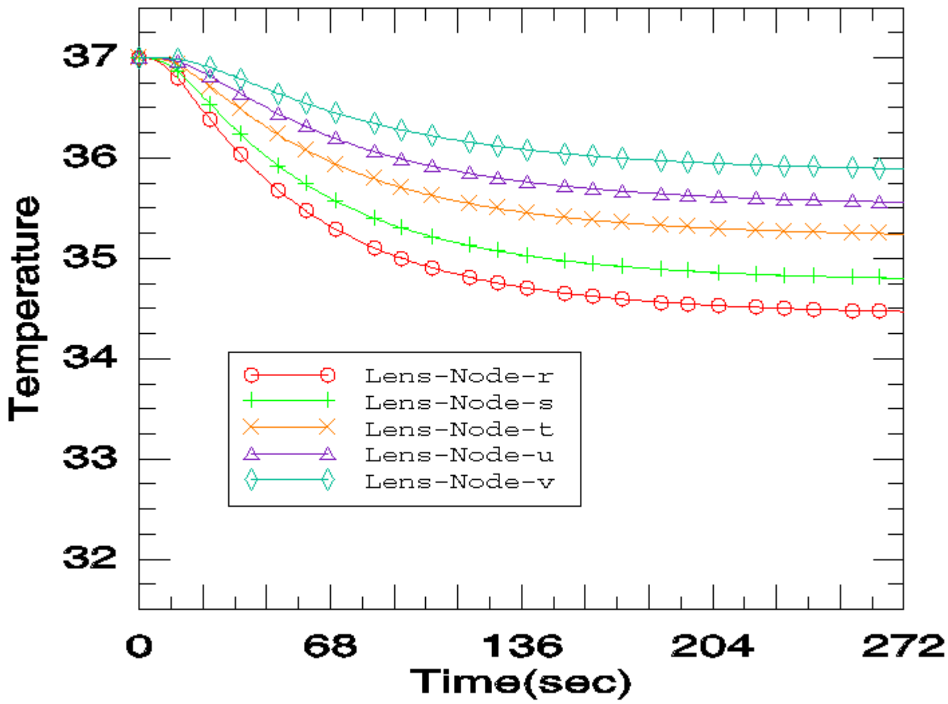

Fig.5.54 Temperature distribution through lens at nodes (r,s,t,u,v)

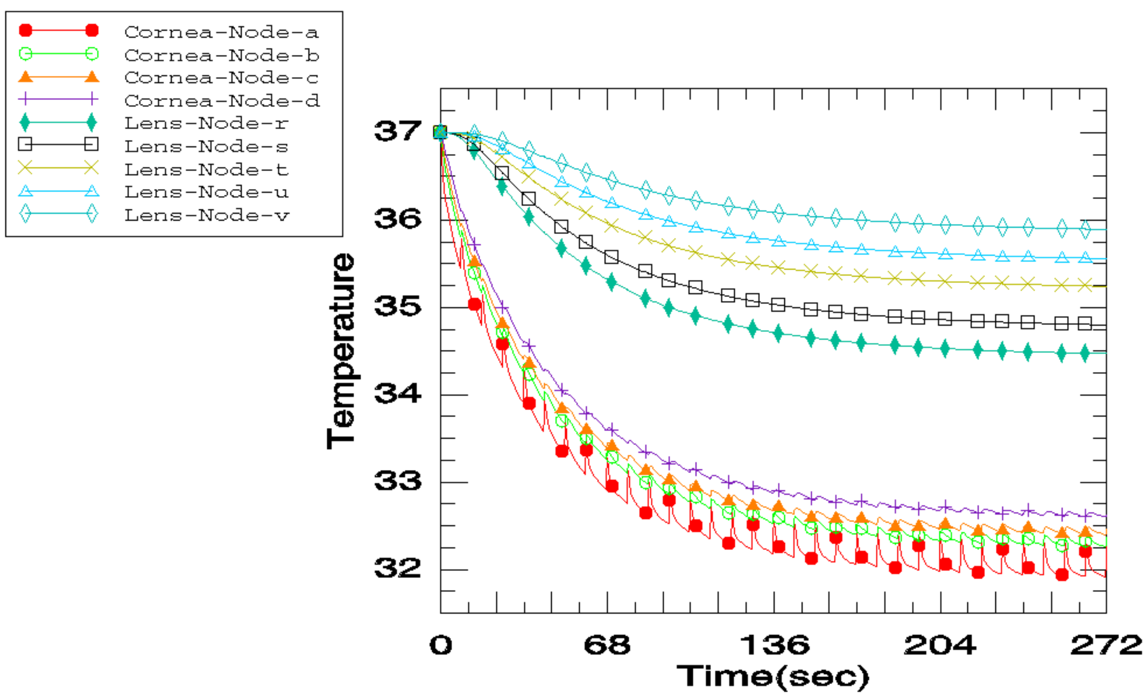

Fig.5.55 Temperature distribution through cornea and lens.

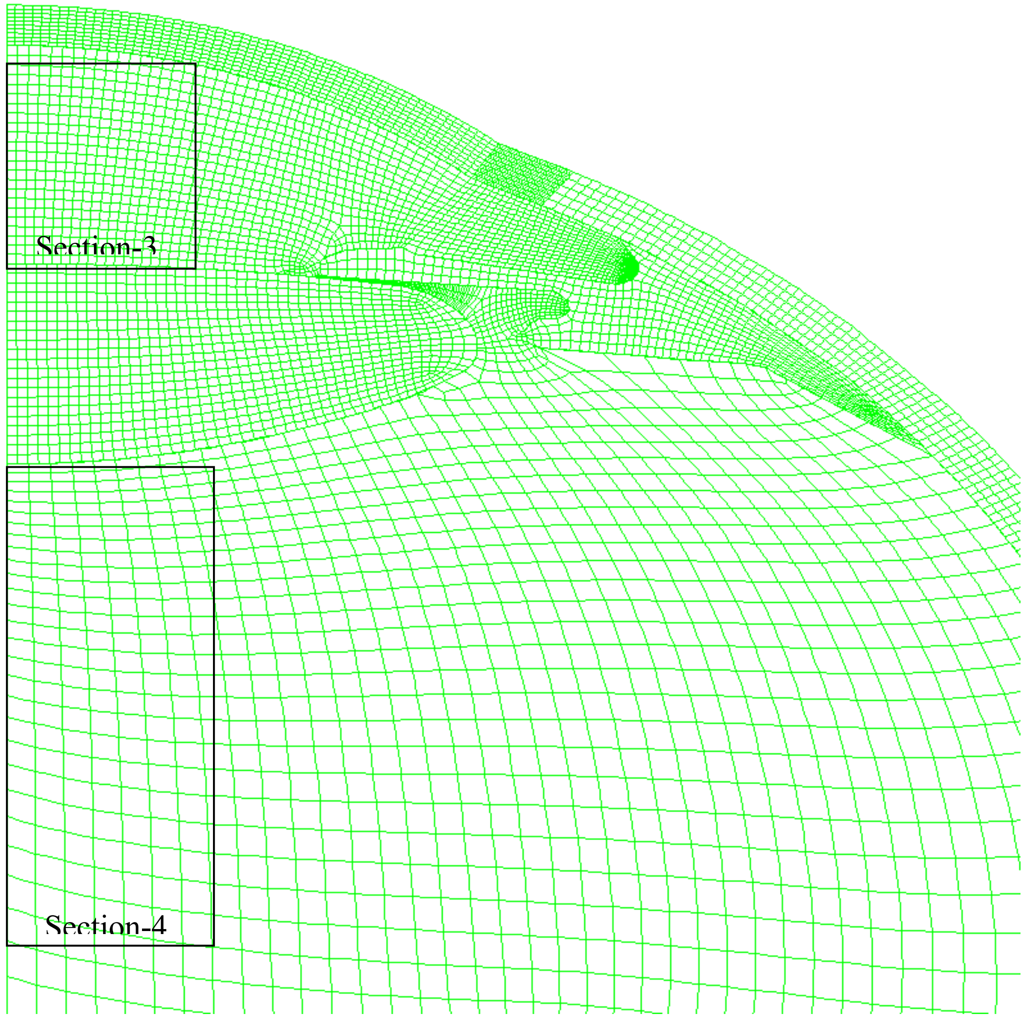

Fig.5.56 Anterior and Posterior part of the eye

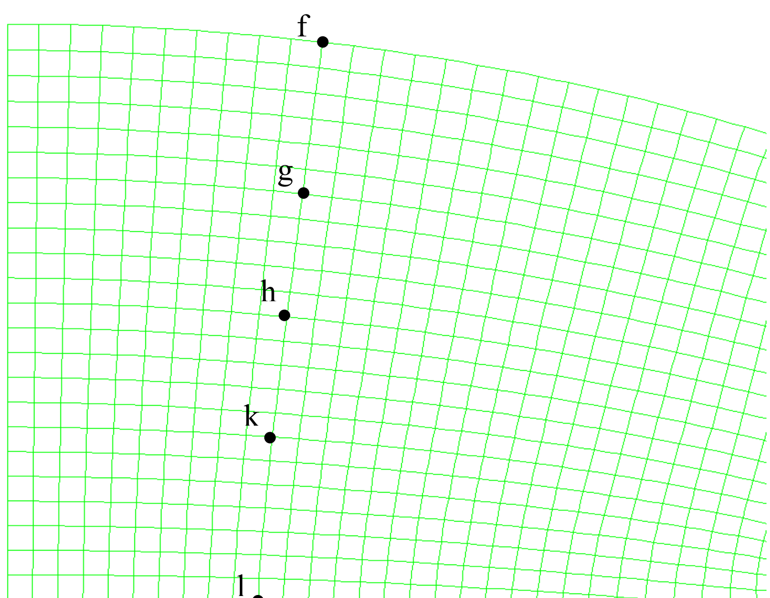

Fig.5.57 Section-3. Anterior part

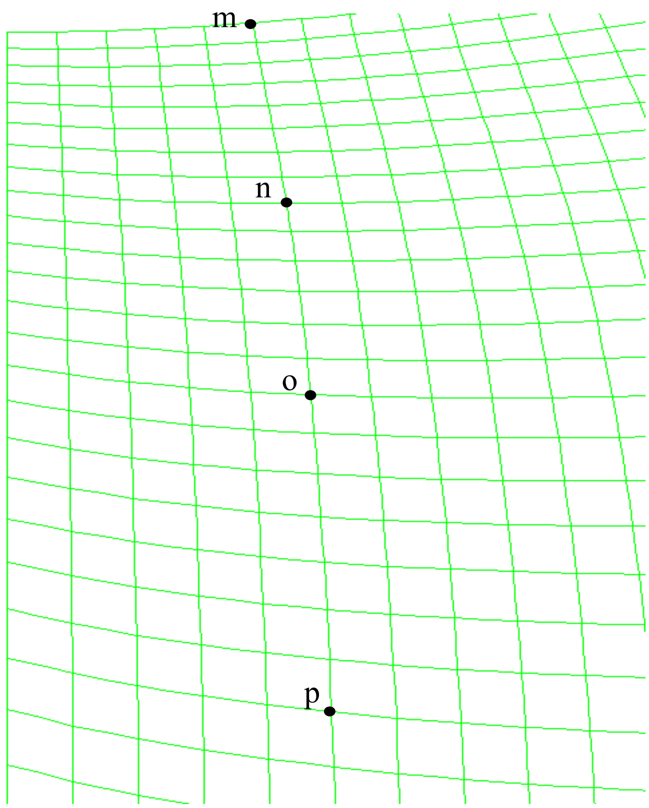

Fig.5.58 Section-4 'Posterior Part'

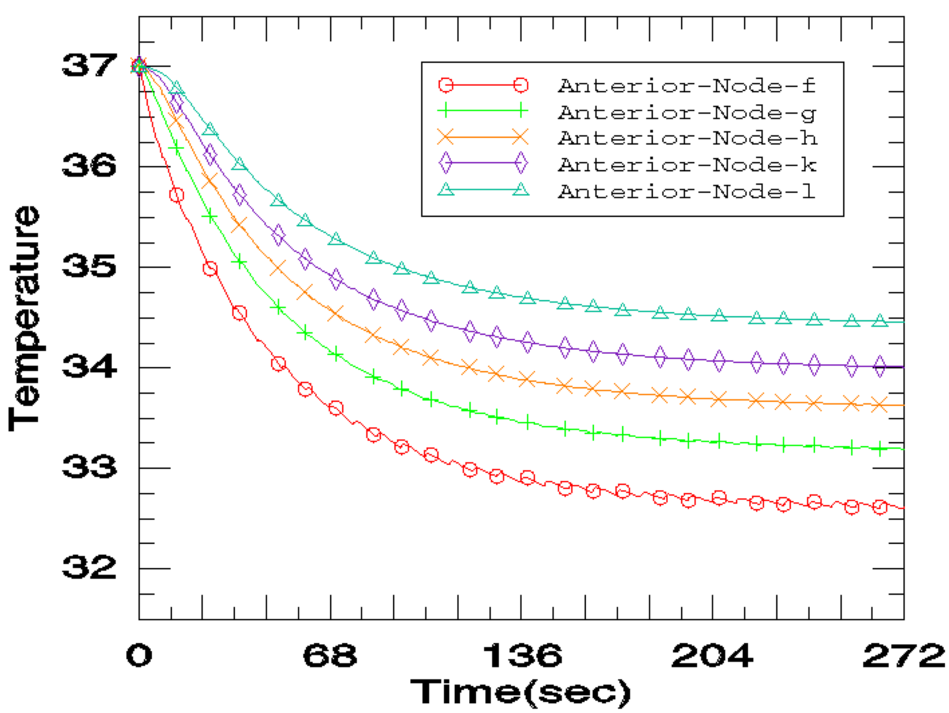

Fig.5.59 Temperature distribution through Anterior Chamber

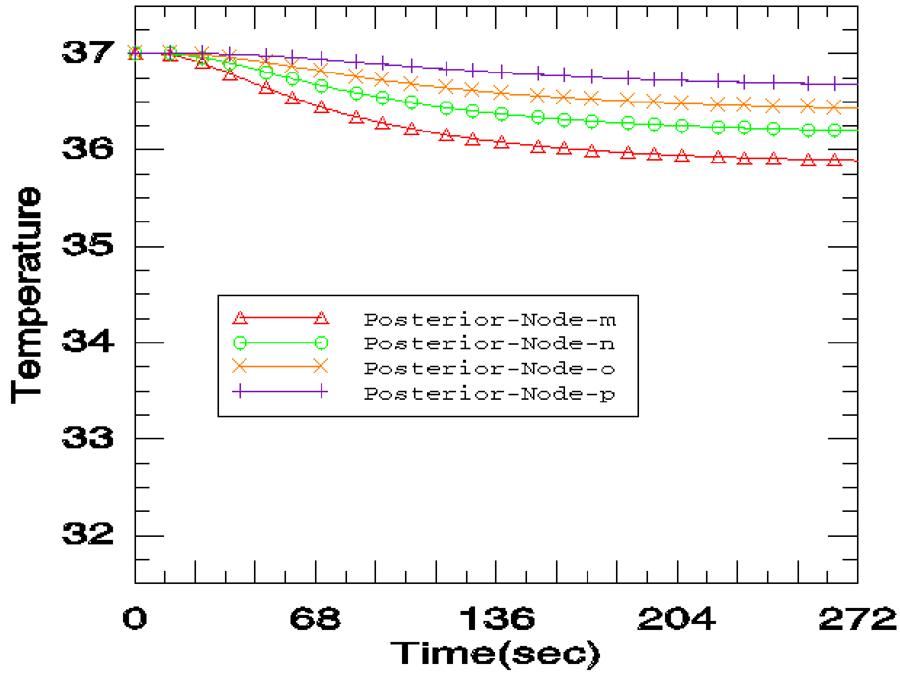

Fig.5.60 Temperature distribution through Posterior Chamber

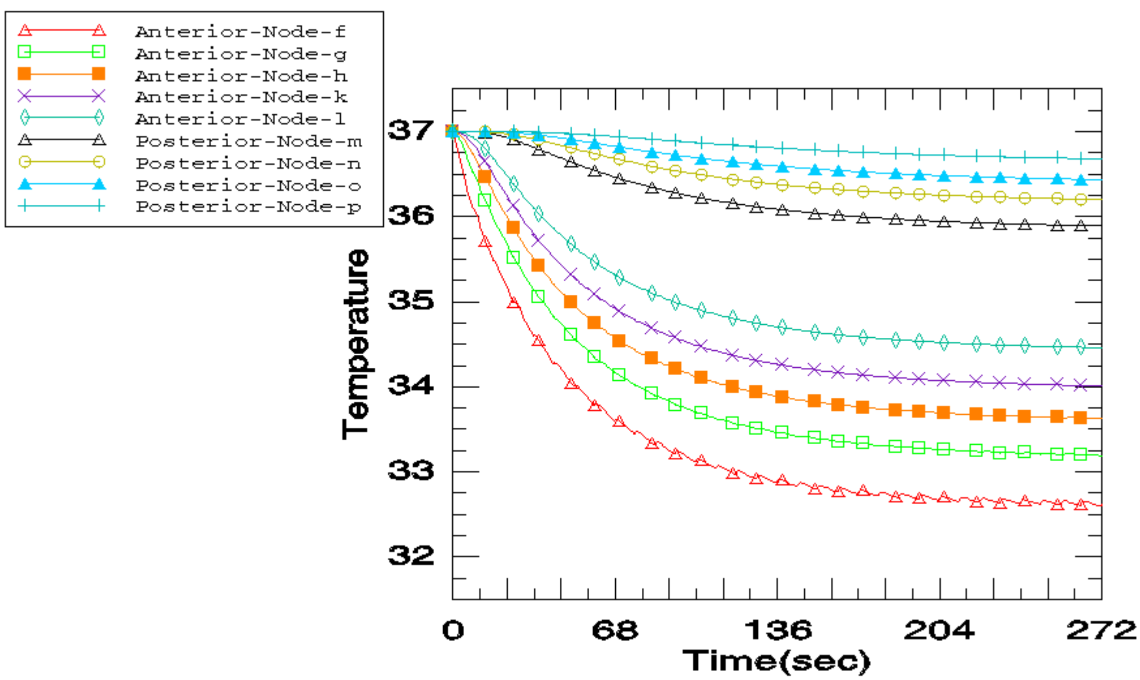

Fig.5.61 Temperature distribution through Anterior and Posterior Chamber

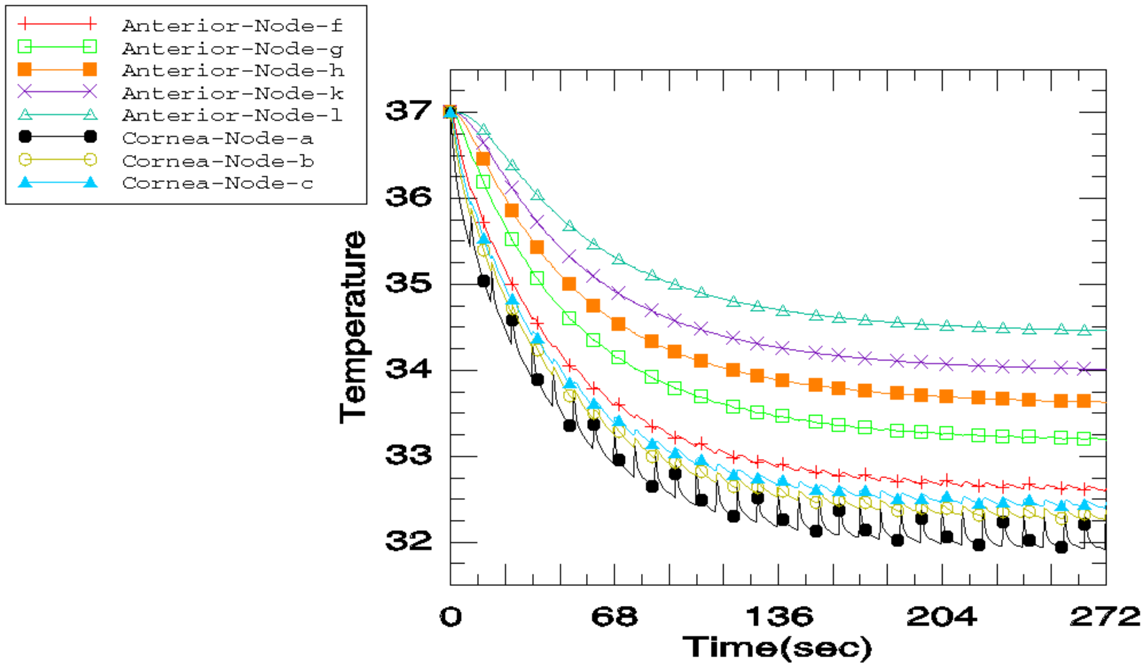

Fig.5.62 Temperature distribution through Cornea and Anterior Chamber

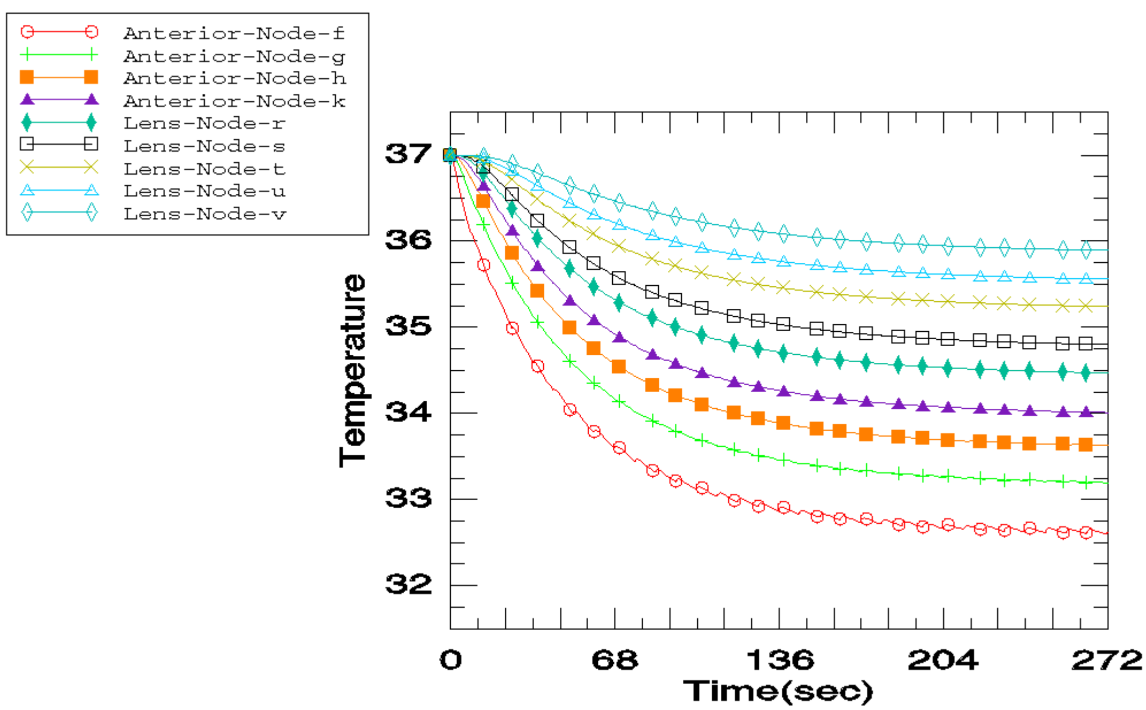

Fig.5.63 Temperature distribution through Anterior-Lens

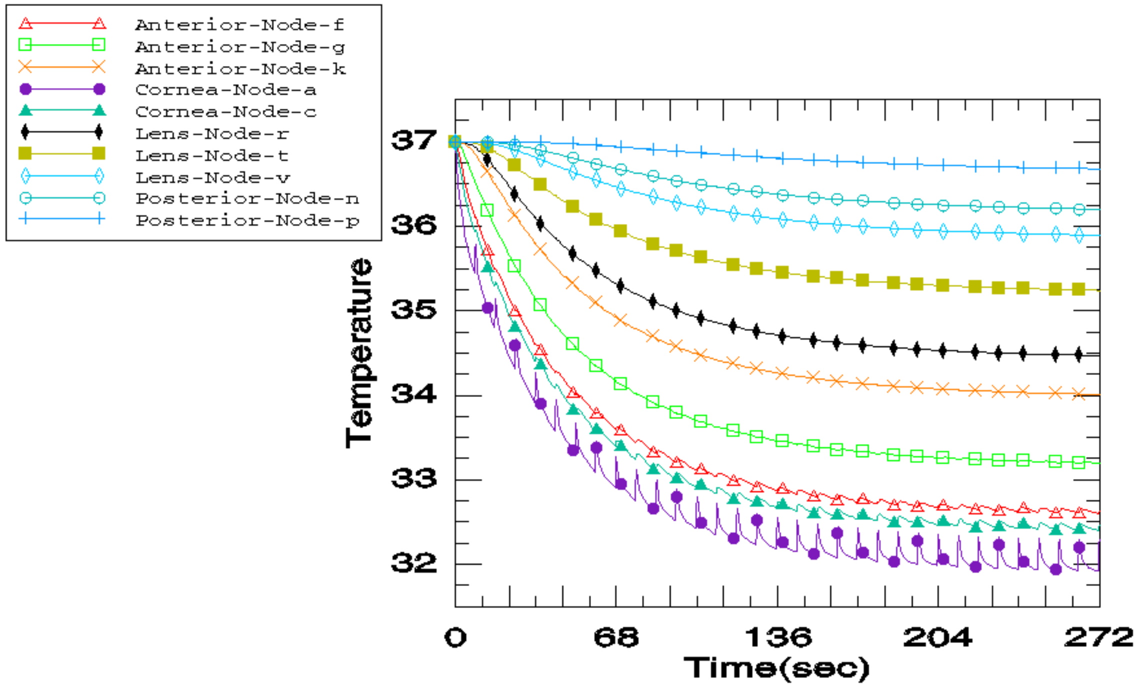

Fig.5.64 Temperature distribution through Cornea-Anterior Chamber-Lens and Posterior Chamber

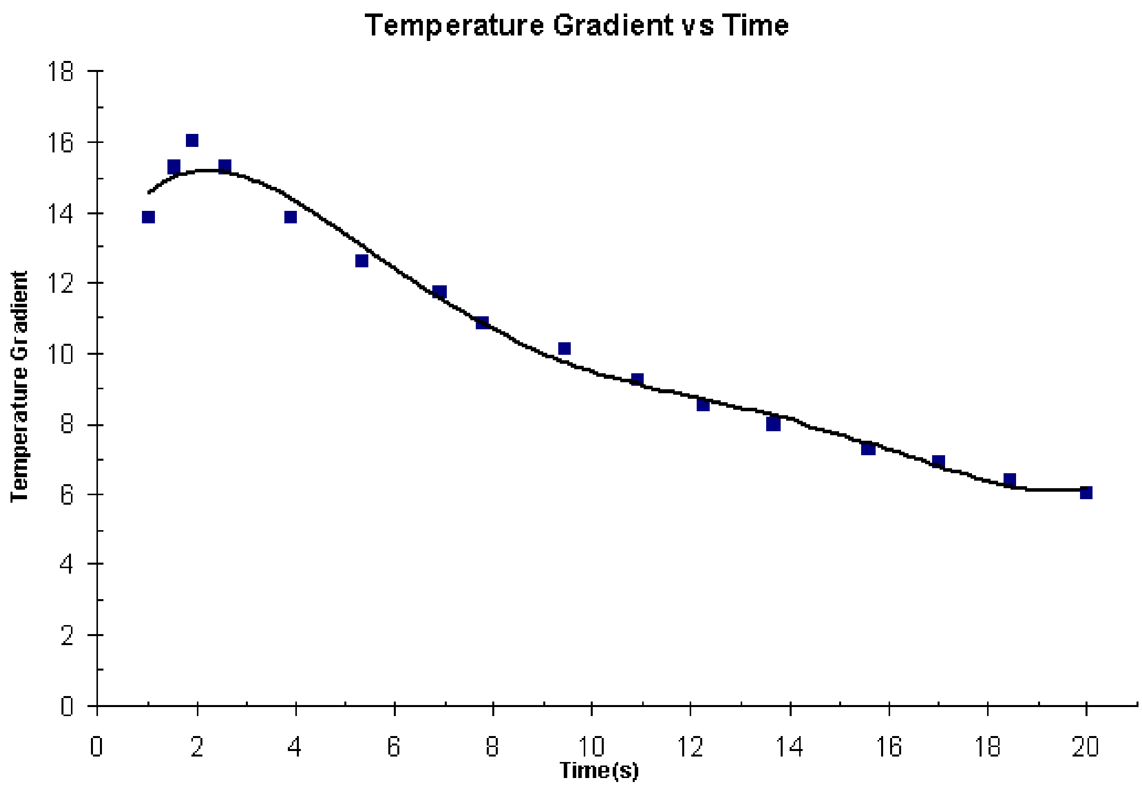

Fig.5.65 Experimental result of the cornea at ($45\,C^o$), Tanelian (1984)

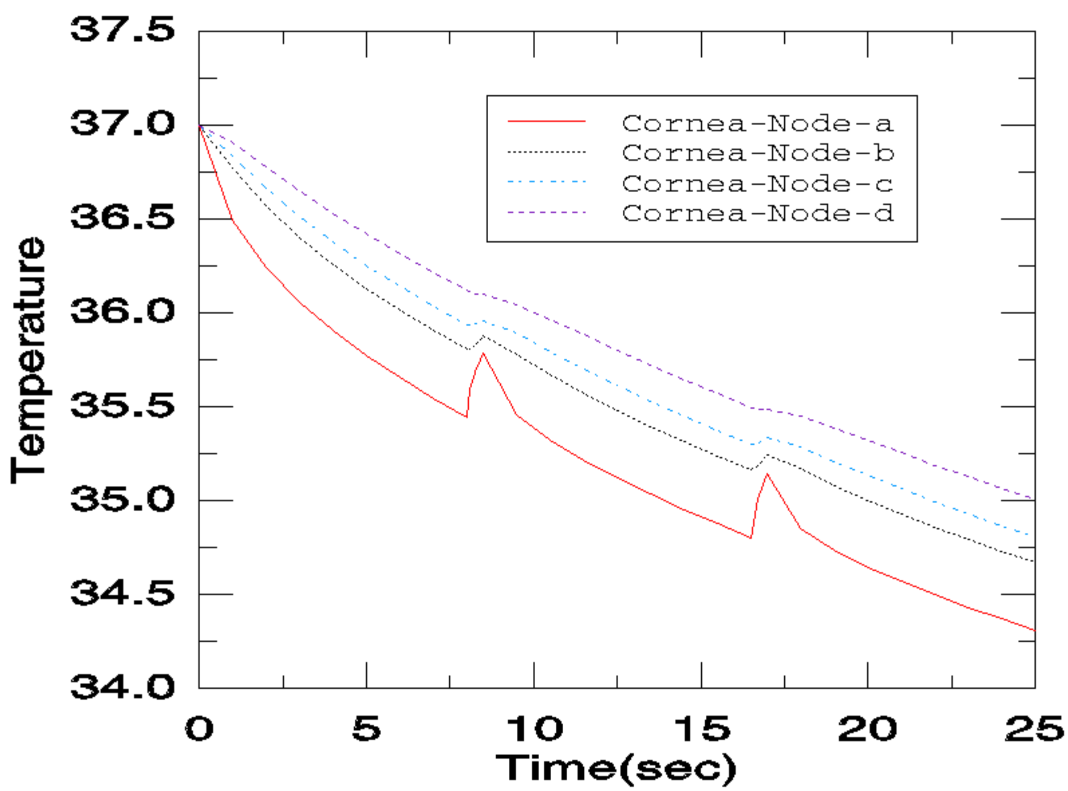

Fig.5.66 Cornea-Temperature vs. Time

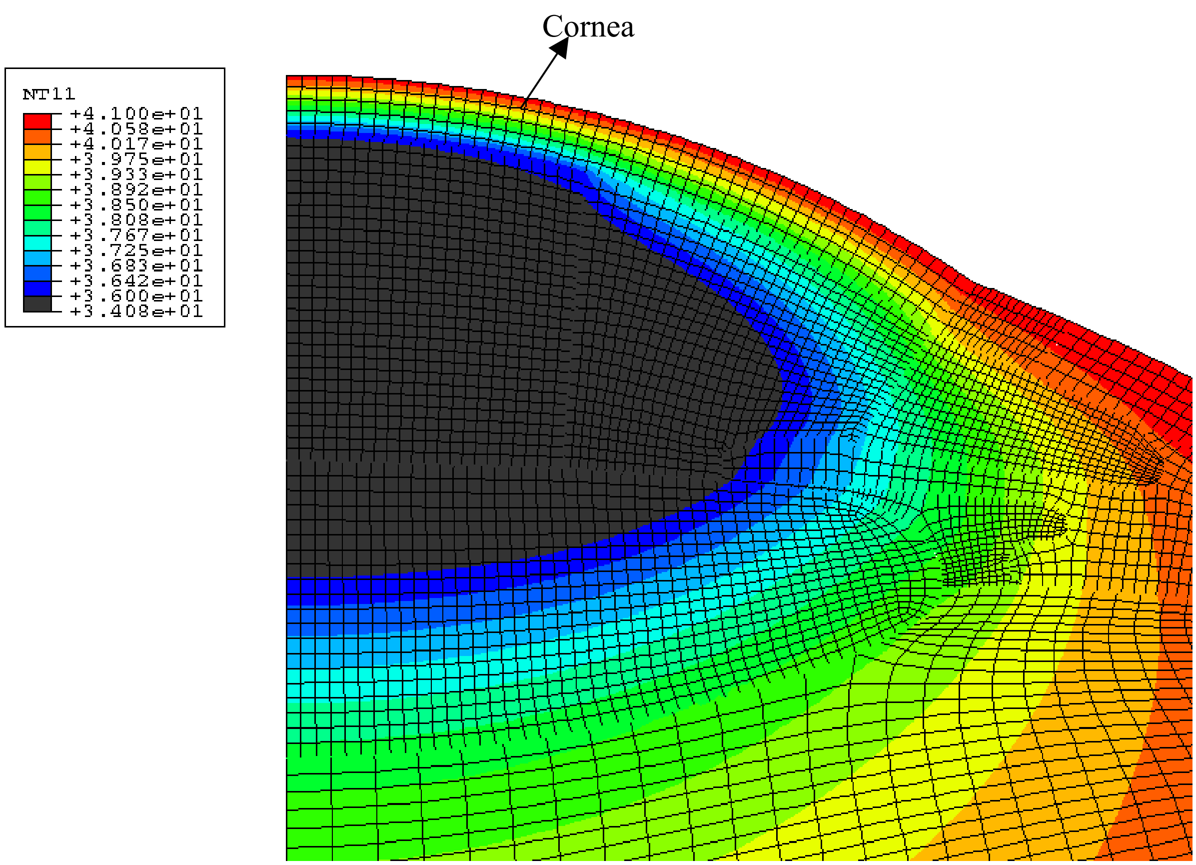

Fig.5.67 Cornea with the eye parts (at 10 seconds)

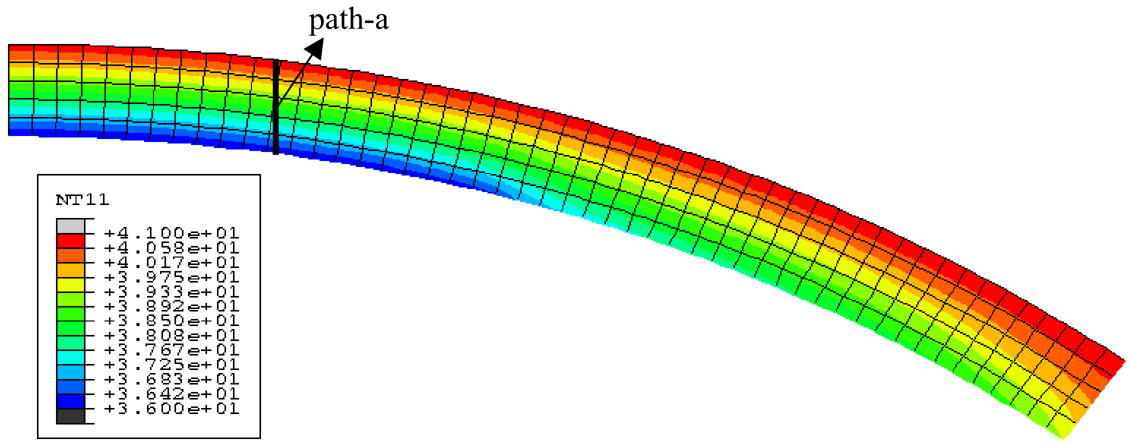

Fig.5.68 Cornea (at 10 seconds)

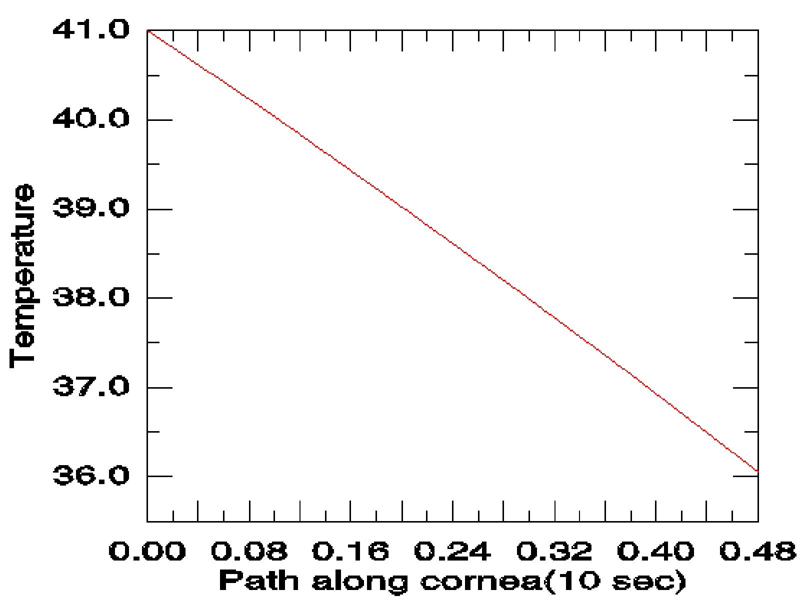

Fig.5.69 Cornea at path-a (at 10 seconds)

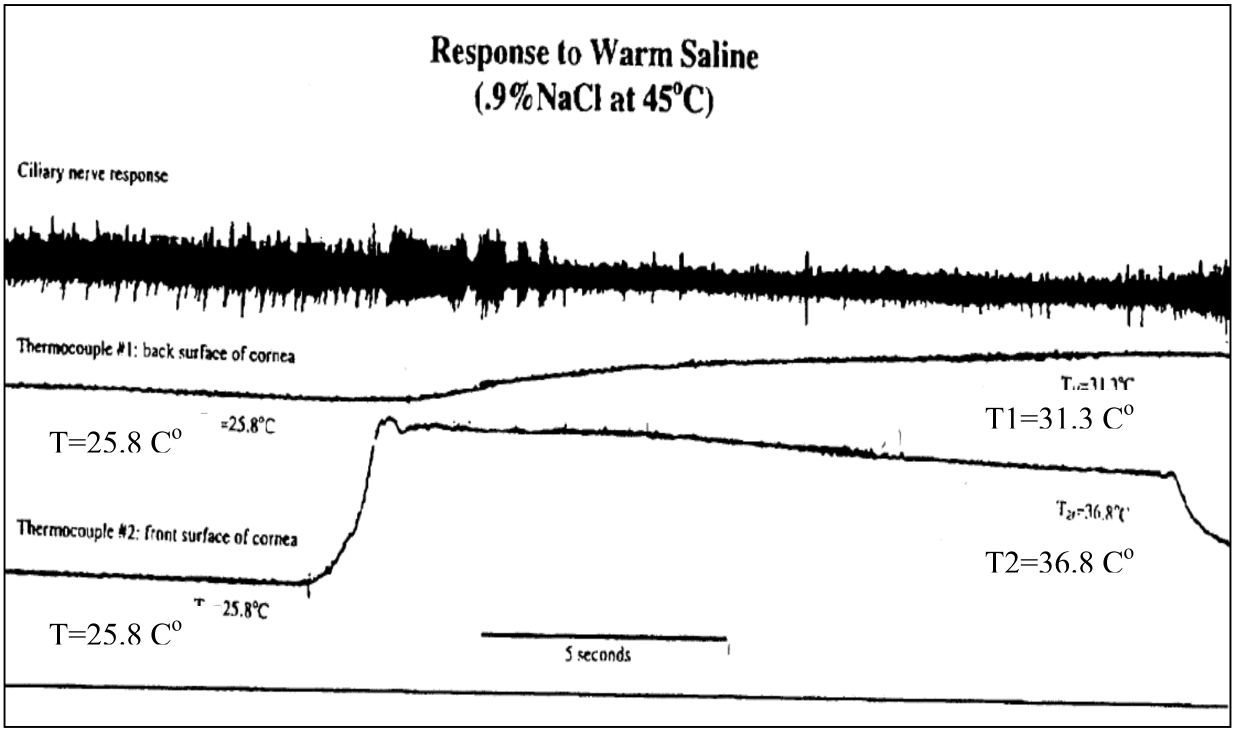

Fig.5.70 Experimental Result (Tanelian and Beuerman, 1979)

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